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Narrative Review Article

# Comparative Review of Fire Growth Models

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## ABSTRACT

Climate change resulted in an increase in wildfire frequency and severity, with hotter climates and drier weather. Along with the wildfire frequency, there is a growing need for wildfire prevention systems and infrastructure. Fire growth models (FGMs) assist in predicting fire behaviors and developing effective countermeasures. This paper reviews various FGMs including Fire Area Simulator (FARSITE), Prometheus, and Cell2Fire, analyzing their methods and doing comparative analysis on their computations and practical uses. Prometheus and FARSITE rely on wave-propagation, yielding results that closely align with real-life wildfire cases. Each model is tailored to its respective region: Prometheus for Canada and FARSITE in the United States. Accuracy is highly dependent on quality of data, particularly wind and fuel maps, which is why they are noticeably less accurate in testing in other regions. Cell2Fire is much faster compared to Prometheus and FARSITE due to its use of cellular automata for faster parallel computing, however with slightly reduced accuracy.

**Keywords:** Fire Growth Models; Computational Modeling; Fire Behavior Prediction; Fuel Modeling; Wave Propagation Models

## INTRODUCTION

In recent years, with climate change intensifying aridity and heat, fires have become exacerbated, increasing in regions including Canada and a large portion of California (1). The 2020 August Complex in California burned over one million acres and resulted in mass vegetation loss, soil erosion, and degradation of air quality. Likewise, the cost of managing wildfires has become increasingly expensive and difficult to maintain (2). Considering this, there have been augmented preventative measures against wildland fires, and fire growth models (FGMs) have become foundational in helping mitigate fire damages. FGMs can predict incoming fires, help with plans for fire roads and fire breaks, and develop around a region to prevent extensive damage. It is essential to evaluate the computational frameworks of tools used to manage and predict the behavior of wildfires. This review aims to compare Fire Growth Model (FARSITE), Prometheus, and Cell2Fire with respect to their computational frameworks (Wave-propagation vs cellular automata), fuel modeling approaches, and practical validation performance across diverse geographical contexts. Prometheus and FARSITE are the primary FGMs utilized in Canada and the US respectively. While both serve the purpose of predicting fire behavior to inform land management, their calculations and fuel management systems which they are built on differ significantly. The objective is to understand the differences behind these models and how these contribute to where they are applied and most useful.

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## COMPUTATIONAL APPROACHES

In creating fire growth simulations, factors including humidity, time, and wind vectors are factored into calculations. Using this data from historical fire datasets, empirical fire behavior models are created to help predict fire spread outcomes and their outputs are used as input for FGMs. As part of the input for empirical FGMs, weather is an essential factor in its calculations. Prometheus and Cell2Fire both utilize the fire behavior prediction (FBP) system, a set of empirical fire behavior models, calculating point data of behaviors of fires. To do this, FBP utilizes the Canadian Forest Weather Index (FWI) . FWI contains six predictive factors (3): Fine fuel moisture code (FFMC), which quantifies the water content of small and fine dead organic matter; Duff moisture code (DMC), which quantifies the water content of medium-sized unconsolidated organic layers in moderate depth; Drought code (DC), which quantifies the water content of deep, consolidated layers of organic matter; Initial spread index (ISI), which estimates the potential rate of fire spread using FFMC and wind speed; Buildup index (BUI), which quantifies the amount of available fuel for combustion, based on DMC and DC values; Fire weather index (FWI), which uses BUI and ISI to quantify the fire intensity, and is used as an index for fire danger in particular fuel-rich areas of Canada (Table 1).

### Prometheus

At the core of Prometheus's calculations is Huygens' principle of wave-propagation, where the fire perimeter propagates around each vertex as its own elliptical "firelet" which uses the Canadian FBP system to determine the dimensions and orientation of each one. Throughout each time step, the rate of fire spread was calculated using the FBP system, then partial differentiation equations were used to compute propagation of vertices (Figure 1).

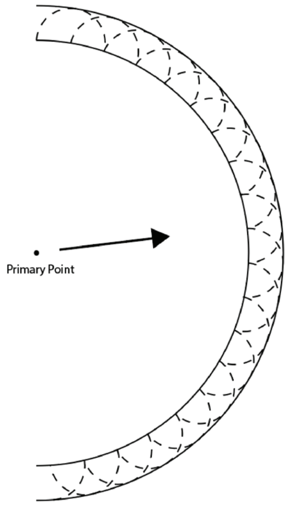

***Figure 1.*** *Conceptual illustration of Huygens' wave-propagation principle applied to wildfire spread modeling[4]. Each point along the fire perimeter generates an elliptical "firelet," and the envelope of these expanding wavelets forms the new fire front.*

### Cell2Fire

Cell2Fire is cell-based, meaning the landscape is partitioned into square cells forming a grid, with each cell containing different topographic fuel characteristics. During each time step, calculations on the head rate of spread, flank rate of spread, and back rate of spread are used to model elliptical fire growth within each cell (Figure 2). Furthermore, these characteristics for rate of spread across the eight adjacent cells is calculated using

***Table 1.*** *Components and input variables of the Canadian Forest Fire Weather Index (FWI) system used in fire behavior prediction (3).*

| Predictive Factor | FFMC | DMC | DC | ISI | BUI | FWI |
|---|---|---|---|---|---|---|
| **Temperature** | ✓ | ✓ | ✓ | – | – | – |
| **Wind** | ✓ | ✗ | ✗ | ✓ | – | – |
| **Rain** | ✓ | ✓ | ✓ | – | – | – |
| **Relative humidity** | ✓ | ✓ | ✗ | – | – | – |
| **Previous predictive index** | – | – | – | ✓<br>FFMC | ✓<br>DMC + DC | ✓<br>BUI + ISI |

*Notes: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index (ISI), Buildup Index (BUI), and Fire Weather Index (FWI).*

the Canadian FBP System as functions of weather, slope, and fuel characteristics, with each cell acting as a new ignition source. Every individual cell serves as a discrete point of origin for further propagation. Using this method, Cell2Fire is able to approximate the elliptical pattern traditionally handled by vector equations in an efficient way. Similar to Prometheus, Cell2Fire uses the Canadian FBP System to assist in simulating spread (5).

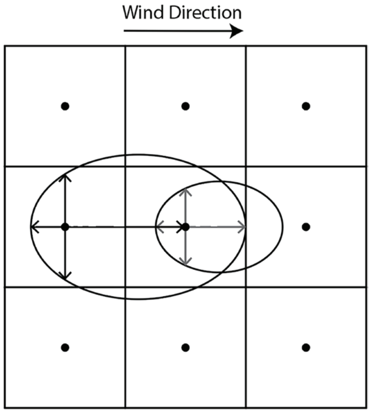

***Figure 2.*** *Elliptical pattern of fire spread$^5$. The landscape is divided into grid cells representing local conditions, and fire spreads through interactions between neighboring cells, as implemented in the Cell2Fire model for improved efficiency and scalability. (adapted from Pais et al.$^5$).*

## FARSITE

FARSITE, like Prometheus, uses equations based on Huygens' wave-propagation technique, where points on a fire's edges become independent elliptical wavelets. During each time step, a new ellipse is created based on conditions of the local environment, including fuel types, height, and wind direction. It inputs raster data from a Geographic Information System (GIS), including elevation, slope, aspect, fuel types, and forest coverage. Rate of spread and fire intensity is calculated using Rothermel's fire spread model using given GIS data. The Rothermel Fire Spread Equation is semi-empirical, meaning it combines theoretical principles with data-backed scaling factors and coefficients retrieved from laboratory experiments. Its empirical evidence shows a relationship to the shape between wind and slope vectors, fuel bed characteristics, and the shape of the resulting fire ellipse (6).

## Model Comparisons

Although all three simulate wildfire spread using elliptical growth patterns, their underlying computations vary in performance, accuracy, and application.

Both FARSITE and Prometheus use Huygens' wave-propagation model as their core mathematical framework, managing the fire perimeter as a continuous expanding physical shape. Their use of Huygens' wave propagation allows them to model fire spread with high geometric precision, making them better suited for forecast planning and behavior analysis. However, this accuracy comes at the cost of increased computational complexity which becomes more difficult as more perimeter points are added over time.

Conversely, Cell2Fire uses a discrete layout of cells for its calculations on landscapes. Rather than tracking a continuous parameter like Prometheus and FARSITE does, Cell2Fire calculates spread through local interactions with neighboring cells. Their method significantly improves the efficiency, thus the scalability of the model compared to Prometheus and FARSITE is improved. This comes with limitations, however, due to the fact that it is essentially a raster-based model lacking the resolution and hence the accuracy of Prometheus and FARSITE, both of which are vector-based models (7).

All models shared characteristic data errors, with fuel and wind vectors being found to be crucial components across most models that were found to have categorical inconsistencies in results. Not only was it crucial in the rate of spread, but with the unpredictability of wind vectors, it was a source of inaccuracies.

***Table 2.*** *Comparative overview of major fire growth models. Summarizes modeling approaches, underlying equations, input data, and key strengths of Prometheus, FARSITE, and Cell2Fire.*

| | **Prometheus** | **FARSITE** | **Cell2Fire** |
|---|---|---|---|
| Growth logic | Huygens' Wave-propagation | Huygens' Wave-propagation | Cellular Automata |
| Primary Equations | Canadian FBP System | Rothermel's Fire Spread Model | Canadian FBP System |
| Key Inputs | FWI factors (FFMC, DMC, etc.) | GIS data (Elevation, Aspect, Canopy) | Grid-based fuel and topography |
| Strengths | High geometric precision | Manages heterogeneous terrain | 15-20x faster processing speed |

## PRACTICAL APPLICATIONS

Cell2Fire's cellular automata framework achieved a 15-20x increase in processing speed over Prometheus and FARSITE. Validation through random weather and ignition scenarios shows that it maintained a ~90% spatial accuracy relative to the other models, and upwards of 90% on the structural similarity index metric to real-world wildfires. Its primary advantage is scalability, allowing for significantly larger simulations. Through its multi-threaded computations, it was able to process large-scale simulations with little to no impact on its processing speed, and its speed makes it more ideal for large-scale planning and uncertainty analysis.

FARSITE was found useful for its fires when tested for validation in the 1994 Horizon Prescribed Natural Fire of Yosemite and 1994 Howling Prescribed Natural Fire Complex at Glacier. Comparing fires simulated in FARSITE with real-life fires via reconnaissance, it was found that FARSITE's simulation of the Horizon Fire was "reasonably accurate", especially with timer and shrub fuels. However, it was also found that the model's accuracy relied noticeably on the fuels and wind types, both of which were difficult to replicate due to the unpredictability of those factors. Furthermore, the Howling Fire was much less accurate as the fuel bed wasn't uniform; something that Rothermel's equations depended on (8). In a more recent 2025 study, FARSITE appeared to underestimate the extent of fire propagation (9). Another study published in 2025 on a wildfire in Madeira Island in 2024 found FARSITE's data useful for building their own platform incorporating satellite weather data (10). Ultimately, the progression of FARSITE shows that Rothermel equations themselves being constrained to its homogenous calculations due to its data collection on homogeneous conditions, its use as a foundational framework allows FARSITE to be used under heterogeneous conditions makes useful for modern utility. The shift from its applications in 1994 towards modern satellite-driven platforms shows an evolution towards convergent modeling, a trend that, if followed, would be a promising direction for future development.

Prometheus was originally created for use in Canada, with fuel types and FBP measuring data from Canadian Wildland fires. Numerous case studies have evaluated Prometheus, particularly on heterogenous landscapes outside of Canada. These studies test the model's ability to accurately simulate diverse wildfires and terrain. A case study on the August Fire Complex focusing on qualitative comparisons found that weather data quality was key to more accurate fire simulations using Prometheus, with lower-quality and lower resolution weather data significantly affecting the outcome of the simulated fire (11).

## CONCLUSION

This paper set out to compare various FGMs, examining their computational structure, inputs, and validations and applications. The methodologies and inputs are similar between Prometheus and FARSITE which both use Huygens' Wave Propagation model allowing it to prioritize accuracy, while Cell2Fire uses cellular automata making it more efficient while also being reliable for large-scale simulations. All models depended largely on input data, with key points being weather data quality and fuel mapping quality, which are large factors in running accurate simulations. FGMs continue to be improved, with advances in technology and calculations allowing for more accurate results and allowing for more synergy with other predictive softwares including real-time weather reporting. To move beyond current limitations, it is recommended to shift towards modeling systems that are dynamic and multilayered. Using established simulation logic to assist in processing high-resolution wildfire data would allow for more responsive and predictive architecture. For example, with the rise of robotic applications for wildfire management, unmanned aerial vehicles could assist in collecting real-time data collection and model validation (12).

## CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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