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Mathematical Modeling of Forest Fire – Comprehensive Review

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Abstract

The goal of forest fire modeling is to understand and forecast the behavior of forest fires through numerical simulation. To simulate fire dangers and fire spread behavior, statistical techniques are applied to historical fire incidents. A number of fire-based data tables are used to create the Canadian fire weather index (FWI). FWI is a straightforward method that effectively identifies vegetation's fire vulnerability. Simple empirical equations are used to calculate the Australian fire danger index (FDI). Similar to FWI is FDI. Models for forest fires that combine stochastic and mathematical techniques accurately mimic the spread of the fire and forecast its severity. Physical models use heat transport through convection and radiation as well as the heat balance of sources (fire) and sinks (forest areas close to the fire source). MATLAB or Delphi programs are used to solve the differential equations relating to heat transfer. The world crown fire modeling experiment's predicted fire spread behavior closely matches the predictions made by mathematical approaches. In real-time forestry, forest landscape, wind speed, ambient temperature and rain fall level are obtained from satellite imagery and weather forecasting and machine learning is used for predicting the vulnerability to forest fire and the rate of spreading of the fire.

Keywords: Forest Fire, Rate of Spread, Fire Vulnerability, FWI, FDI, Cellular Automata, Physical Model

1. Introduction

Wildfires are a complicated phenomenon including the interplay of climatic factors, weather pattern, land use, and urban sprawl, as well as issues of racism, equity, and inclusion. Fires nowadays are not like those that occurred in the 1990s, 1970s or 1950s. Fires are burning quicker and hotter than ever before, and complicated socioeconomic variables are causing an increase in the number of people affected by smoke, debris flows, and other wildfire effects. It is becoming increasingly usual for areas to have a catastrophic wildfire after recovering from a previous wildfire. During recent past (year 2022), thousands of people were forced to evacuate throughout the year, and hundreds of people perished by wildfires. Hundreds of more peoples died as a result of the intense heat waves. This year, temperatures in many countries' capitals reached 40-year highs. UNO warned of more forest fires due to hot climates. To add more, many forest fires burned nearly 2 Million Hectare in year 2022. In year 2021, 9.3 Million Hectares of wildland areas were burned by fires that was little troublesome year of wildfires. Some countries/regions use the phrase "forest fire," which will be used where applicable, but "wildfire" is an umbrella term that encompasses all types of wild land fires [1,2].

When we analyse about the origin of fire, it started at the lightning struck the tree and set it ablaze, there has always been fire on earth, and we can be certain that it will continue to exist for a very long time to come. Every living thing on earth experiences a natural fear of it, but only humans have figured out how to manage it and make use of it to improve human welfare. Nevertheless, even people occasionally find themselves unable to manage a fire, which can result in serious harm. Fire spreads by gradually changing the condition of each fuel cell that is dispersed throughout space over time. Fuel which in this instance only refers to vegetal particles that are alive or dead, is commonly referred to as forest fuel. Fuel is the stuff that is subject to burning. The generation, transport, and absorption of heat occur gradually as one status transitions to the next, depending on the surroundings and fuel available at each step. Thus, taking a gander at the fundamental plan of wildfire spreading, there exist three essential cycles that are expected to display fire ways of behaving and thus to control it, viz, creation of warmth by heat sources basically because of ignition of unburned material, heat move from heat sources (fire) to warm sinks, and retention of heat by heat sinks (fuel ahead, ambiance air, soil, and so on) [1,2].

In order to understand fire behavior and also to obtain primary data for fire models, many world scientists jointly planned and conducted the International Crown Fire Modeling Experiment (ICFME) in Australia. For evaluating models, the fire trials yield a wealth of helpful information. Many theoretical papers compare model predictions with the data from this ICFME experiment called “F19”. The meda grass (also known as kangaroo grass) covered the 200m x 200m plot in F19. On the plot's upwind edge, a 175-meter-long igniting line that was parallel to the direction of the wind was used to start the fire. Two fieldworkers walked 56 seconds (87.5 meters) in opposing heading from the middle highlight the stopping points fire carrying drip torches to start the line fire. Scientists' observations of continuous and homogenous grass layers are helpful to others to apply triangular network with 91% vegetation. Before a fire, the sizes of the vegetation's components were estimated, and experimental flame height observations were made. All through the fire, estimations of the breeze speed at 2m above ground level (AGL) at each side of trial plot were made every 5s. At the times t=56s and t=86s, fire perimeters are plotted to measure the rate of spread (ROS) [3-5].

Similar to aforesaid Australian ICFME experiment, scientists from the USA, Canada, and Russia participated in another ICFME in Canada. This ICFME aimed to tackle the issue of high-intensity fire behavior prediction. In order to quantify the factors necessary to model the initiation and spread of crowning flames, the ICFME conducted a replicated series of extensively instrumented crown fires. The study site was in Canada's Northwest Territories, close to the Fort Providence area. This area of grassland has a jack pine stand that is about 80 years old with lush grasses. Ten fire plots had their aerial, surface, and forest floor fuels sampled. Each plot had fire lines that were roughly 50m wide, which were created by felling and removing standing trees and bulldozing to mineral soil to make it easier to access and control fires. On some plots, some fuel processing (tree pruning and or removal of surface fuel) was done, but the majority of the area as such. This ICFME was done during 1995-2011 to get detailed on forest fires. ICFME data is very useful to verify mathematical models validity. Before ICFME experiments, wind tunnels were used to manipulate fire behavior and rate of speed (for example, C064). This review article aims to present forest fire models briefly. The models are explained by taking typical examples from empirical (statistical) models and physical (analytical) models [3-5].

2. Materials and Methods

This review article depends on secondary data. Data were gathered from journal and conference articles. Fire weather index, fire danger index, international crown fire model experiment, artificial intelligence (machine learning) of the forest, Huygen's principle of wave propagation, cellular automata of propagation, stochastic random walk of fire particles, probabilistic random walk of fire particles, fire propagation models, coupled fire-atmospheric weather models, fully heat transfer based physical models, semi-physical models based on grassland fire experiment and heat balance has been applied in past study to get the seriousness of forest fires and anticipate the event of out of control fires and decrease the adverse consequences of fires on the eco-system and people. These statistical old fire data, empirical equations put forth by scientists and theoretical models proposed by technologists help us in determining accurately the fire severity or vulnerability of forests and grasslands to fire and the rate of fire spread in assisting our efforts to take precautions to conserve and protect natural supply sources and ourselves. In real-time forestry, satellite and fire station systems are used in conjunction to manipulate the climate and wind and calculate the size and state of the fire events and in turn to act in advance to protect forests. The current survey is on the data assessment through the fire modeling that gives us data about fire propagation speed [1,2].

3. Results and Discussion

3.1. Modeling of Wildfires

Wildfires are one of the disasters that threatened the world with heavy loss by burning millions of acres of forest land and by damaging flora, fauna, and humans. As told in the introduction section, world lost 9.3 hectares in the year 2021 by wildfires. Table 1 lists some important wildfires that challenged the human race with their devastating power.

Table 1. Largest Wildfires in the World History

S.No	Wildfire Name	Country	Year	Area Burned (Millions of Acres)
1	Siberian Taiga Fires	Russia	2003	55
2	Australian Bushfires	Australia	2019 & 2020	42
3	Northwest Territories Fires	Canada	2014	8.5
4	Alaska Fire Season	USA	2004	6.6
5	Black Friday Bushfire	Australia	1939	5
6	The Great Forest Fire	Canada	1919	5
7	Chinchaga Fire	Canada	1950	4.2
8	Bolivia Forest Fires	South America	2010	3.7
9	Great Fire of Connecticut	USA	1910	3
10	Black Dragon Fire	China & Russia	1987	2.5
11	Richardson Backcountry Fire	Canada	2011	1.7
12	Manitoba Wildfires	Canada	1989	1.3

Nowadays, 85% of wildfires are anthropogenic and in recent years 57% rise in wildfires are noted due to the very hot climate prevailing everywhere. As told in the introduction section, fires are more and fast now. To answer "how fire spreads?", during the fire, fuel combustion results in the creation of heat, which is a type of energy once a portion of the land has burned. When the circumstances are appropriate, heat is passed to adjacent particles, which use the energy first for evaporation before being ignited. To answer "what influences wildfire?", as depicted in Figure 1, three elements influence how a fire spreads through a region. To model fire spread behavior, a quantitative understanding of these parameters on fire spread is essential [6-8].

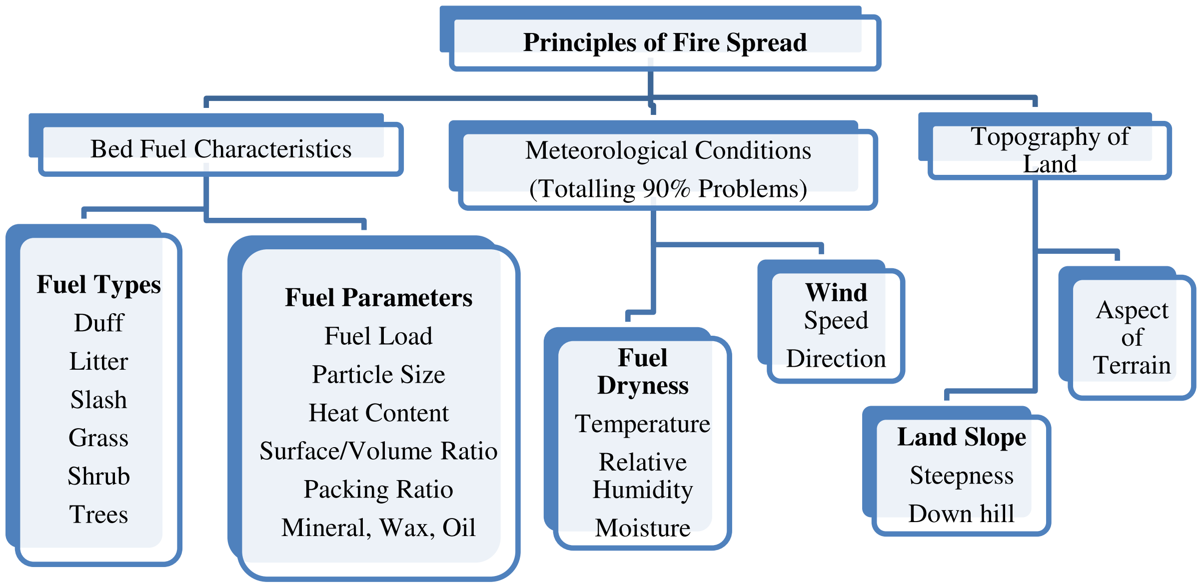

Figure 1 Wildfire spreading parameters

As illustrated in Figure 2, a variety of fire spread models have been presented using a variety of methodologies that are categorized according to their approach as statistical, semi-empirical, analytical, and semi-physical models. By making the assumption that local uniformity (limited to certain segments of the fire perimeter) exists, computational approaches are utilized in automating the application of fire spread models to more non-uniform situations [2,8].

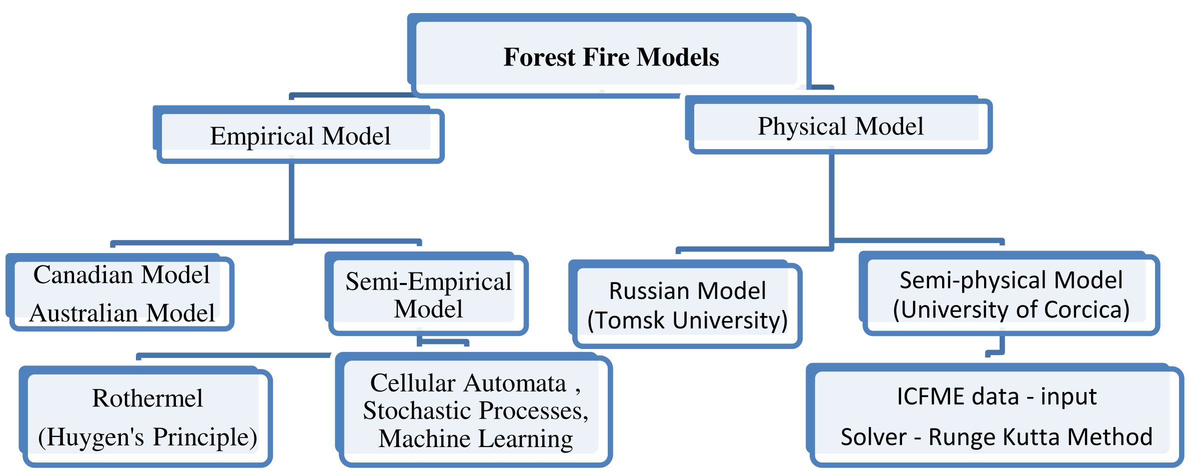

Figure 2 Fire models and simulators

3.2. Statistical Fire Modeling

Forest fires are very common in Africa, North America, and Australia. However, fires are noted many times in Asian regions such as Russia, China, and Arabia too. So, modeling fire and suppressing is better than controlling it. The first important model is the empirical (statistical) model originated to suppress Canadian wild-land fires. It is also known as Fire Weather Index (FWI). The severity level of fire is arrived from old data, as shown in Figure 3. This model calculates FWI from ambient temperature, relative humidity of the atmosphere, wind speed, and rain fall level.

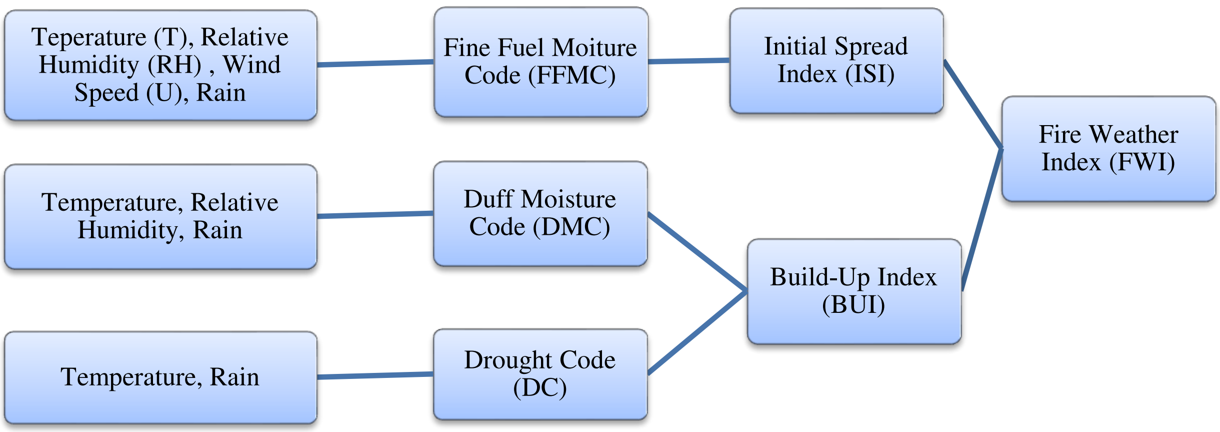

Figure 3 Fire Weather Index (FWI)

To answer "how FWI is obtained?", it is calculated by measuring Ambient Air Temperature and Relative Humidity at local time 12am and at a height of 2m height from average ground level (AGL), by measuring Wind Speed at 12am and at a height of 10m from AGL, and by measuring the daily snow depth and precipitation totaled over 24hours (nothing but Yesterday's reading). FWI is obtained using tables formulated by solving a series of empirical equations. Alternatively, FWI is obtained from online calculators such as or glff.mesowest.org or the R language program. FWI of Canada is a very simple statistically calculated parameter that tells clearly advance fire warnings. McArthur of Australia is credited for his contribution to the Australian Model, another set of empirical equations. It is also known Fire Danger Index (FDI). Australia contains more grasslands and bush-lands that are often met with fire disaster. Australian scientist McArthur's fire model is summed up by single equation. Grassland index (GFDI) is calculated by using Equation 1.

$$GFDI = 2e^{(-23.6+5.01lnC+0.0281T-0.226\sqrt{RH}+0.633\sqrt{U_{10}})} \quad (1)$$

Where T-Air Temperature (°C), C-Degree of Curing(%), RH-Relative Humidity (%), U_{10}-Wind speed in km/h measured at 10m height. Forest index (FFDI), in general for all types of forest, is obtained using Equation 2.

$$FFDI = 2.0\,e^{(-0.450+0.987lnD-0.0345RH+0.0338T+0.0234U_{10})} \quad (2)$$

Where D-Drought factor (0<D≤10) Table 2 correlates calculated fire indices to fire severity levels [2,9]

Table 2 Correlation between Fire Indices and Vulnerability to Fire

Fire Severity level	Danger is in Very Low level	Danger is in Moderate level	Danger is in High level	Danger is in Very High level	Danger is in Extreme level
FFMC	up to 80.9	81.0-87.9	88.0-90.4	90.5-92.4	above 92.5
DMC	up to 12.9	13.0-27.9	28.0-41.9	42.0-62.9	above 63
DC	up to 79.9	80.0-209.9	210.0-273.9	274.0-359.9	above 360
ISI	up to 3.9	4.0-7.9	8.0-10.9	11.0-18.9	above 19
BUI	up to 18.9	19.0-33.9	34.0-53.9	54.0-76.9	above 77
FWI	up to 4.9	5.0-13.9	14.0-20.9	21.0-32.9	above 33
GFDI	up to 11.9	12-24.9	25-49.9	50-99.9	above 100
FFDI	up to 11.9	12-24.9	25-49.9	50-74.9	above 75

Pope's Lagrangian probablility density function (PDF) method is best suited to model turbulent flows. Considering fire spread as a turbulent flow, many scientists have modeled the fires by stochastic process concept [10,11]. In all stochastic / probabilistic models, "Fire Stochastic Particle Integrator" and the random walk of fire particle have been modeled well by Equations 3-6. In this method, heat release and flame propagation are modeled in two-dimensions (2D) and three dimensions (3D). 2D version is presented briefly.

$$\frac{dY_{st,p}}{dt} = -\frac{Y_{st,p}}{\tau_{mem}} \quad (3)$$

$$dX_{i,p} = F_l U_{i,p} dt, where\ i = 1,2 \quad (4)$$

$$dU_{i,p} = -\frac{(2+3C_0)}{4}\frac{u'}{L_t}\left(U_{i,p} - U_{w,i}\right)dt + (C_0 \varepsilon dt)^{1/2} N_i \quad (5)$$

Where $Y_{st,p}$- "burning state" of a particle (its value 0 to 1), τ_{mem} – memory timescale (determining the decay speed and is a model parameter), $X_{i,p}$- coordinate of the fire particle in i^th direction , $U_{W,i}$- wind speed in direction i, $U_{i,p}$- velocity in direction i (of the wind), F_l-scaling parameter (≈0.1), Co-constant (≈2), u'-turbulent fluctuations in velocity, Lt-total length scale, ε-$(u')^3$/Lt, and Ni – a random number variable ditributed with a mean of zeo and variance one.

$$\left.\begin{aligned} dX_{1,p} &= L_r cos\theta_r \\ dX_{2,p} &= L_r sin\theta_r \end{aligned}\right\} \text{where } \theta_r = \xi \quad (6)$$

Where ξ - random variable that has a uniform distribution in 0-2π The radiating particle's $Y_{st,p}$ obeys Equation 3 and has a decay scale $\tau_{mem} = \frac{Lr}{Sf,0}$ where $S_{f,0}$ is diffusing speed equivalent to 0.1m/s, but it varies with space or situations. L_r=10m was used in the calculation. Fire spread was modeled by cellular automata idealogy. Table 3 records the fundamental modeling indicators and their numerical values for basis calculation. Recreation of the Marshall island wildfire (December 2021) was done 100 percent accurately by this crossbreed stochastic Lagrangian-cellular automata model. As it is a review article on all models, derivations, equations and variables are not explicitly presented, some are presented for clarity and others are omitted as they are less important to mention here.

Table 3 Model parameters and their numerical data for calculation

Parameter	Symbol	Baseline value
Fire particle velocity factor	F_l	0.15
Time scale for memory (s)	τ_{mem}	10.0
threshold of burning state	Y_{lim}	0.2
burning state - initial	Y_{init}	1..00
length scale of turbulence (m)	Lt	80.0
intensity of turbulence	A	0.4
Total No. of particles in each cell	Np	20.0
delaying time for ignition(s)	τ_{ign}	30.0
Total burning duration (s)	τ_{burn}	30

.0

In another stochastic approach, Self-Organized Criticality (SOC) was used for forest fire model (FFM) [12]. It is a probabilistic method that the output is briefly given in the form of Figure 4. In this diagram, Savg-average tree cluster size, Smax-maximum cluster size, ρ-density of tree, and L- calculation are side length and θ-asymptotic function (that influences on ρ). Savg was plotted against ρ where Savg is average cluster size (also knows cell size). Smax was plotted against ρ where Smax is maximum cluster size normalized with total number of tress in the calculation area.

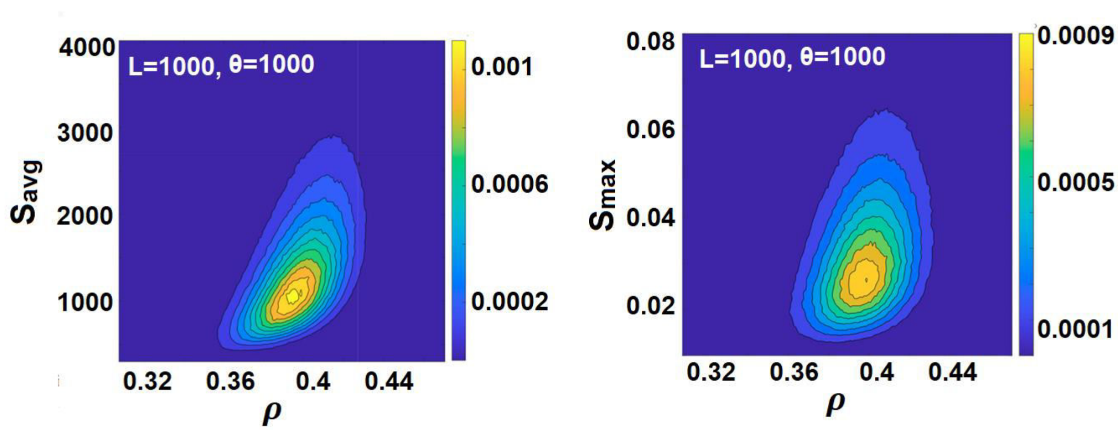

Figure 4 Heat map of SOC based FFM model

3.3. Analytical Fire Modeling

Grishina of Russia (Tomsk College) and Albini of USA irrespective proposed a 100 percent insightful or actual fire spread model that considers the fire fuel collaboration - warming, drying, pyrolysis, and burning [13]. The model uses the preservation of mass, impulse and energy in both the strong and gas stages. The model utilizes a solitary spatio-temporal aspect and it likewise utilizes first-request Arrhenius response chemistry to simulate pyrolysis and burning. During the improvement of the model it was presumed that tempestuous vehicle processes in the vegetation can be demonstrated utilizing tumultuous exchange. The woods are counted as a multiphase, multi-storied, and spatially inhomogeneous medium external the fire zone. Inside the fire zone, the woodland is viewed as a porous scattered, seven-stage, two-temperature, single-speed, responsive medium.

The six stages inside the ignition zone are: dry natural matter, water in fluid state,strong outputs of fuel pyrolysis, debris, gas, and particles in the scattered stage. The heat flux q is expressed as $q = \lambda_T \frac{\partial T}{\partial t}$, where λ_T-eddy diffusivity (effective turbulent conductivity), and T-temperature. Then, the equation for energy balance is given by

$$\sum\left(\rho_i \varphi_i C_{p_i} + \rho_{C_p}\right)\frac{\partial T}{\partial t} + \rho_{C_p} W \frac{\partial T}{\partial x}\left[\lambda_T \frac{\partial T}{\partial x} - H(T - T_\infty)\right] \tag{7}$$

Where ρ_i – fuel density, φ_i – volume fraction, C_{p_i} – specific heat, ρ_{C_p} – gas phase desnity, W-relative humidity, and H-enthalpy. The totalization term incorporates four terms which address dry organic matter, fluid water, consolidated pyrolysis items and the mineral synthesis of the fuel. The convective cooling is contained with the term H(T-T_=), this underscores the way that the model does exclude the hydrodynamic parts of intensity stream, just the ignition. No data about the version of the model (concerning test fires or exploratory flames) was found. Differential Equations are coded in Fortran or Delphi and solved. It is a direct physical model and so approximation methods such as FEM or CFD are not used.

An interesting recent physical model is by Drissi of France (University of Corcica) [3]. He applied the conservation of energy to a fixed volme (control volume), Vj of cell *j that is* exposed to totally Nbc burning plot cells (i=1-Nbc) yields

$$\sum_{i=1}^{N_{bc}}[q^+_{rad}(i) + q^+_{conv}(i)] = q^-_{conv}(j) + \begin{cases} \rho_{WFF} C_{PWFF} \alpha_k \dfrac{dT(j)}{dt} \; for\ T(j) < 373K \\ -\rho_{DFF} L_{vap} \alpha_k \dfrac{dFMC(j)}{dt} \; for\ T(j) = 373K \\ \rho_{DFF} C_{PDFF} \alpha_k \dfrac{dT(j)}{dt} \; for\ 373K < T(j) < T_{pyr} \\ \rho_{DFF} L_{pyr} \alpha_k \dfrac{dFPPC(j)}{dt} \; for\ T(j) = T_{pyr} \end{cases} \tag{8}$$

Where Nbc-total number of burning cells, $q^+_{rad}(i)$ – radiant energy per unit volume and per unit time get by cell numbered j from the all nearby flaming cells($i = 1\ to$ Nbc), q^+_{cov} – convective energy that is received by j from the burning cells (i=1-Nbc), $q^-_{con}(j)$ - radiative energy or heat loss from the fuel bed cell j to the ambient surroundings, T(j) – temperature of cell j, ρ_{WFF}- density of wet file fuel particle, C_{PWFF}– specific heat of wet fine fuel particles,α_k– surface / volume of fine fuels, ρ_{DFF} - density of dry file fuel partice, Lvap - specific vaporization enthalpy at 373 K,, FMC(j) - moisture content of cell j fuels elements, C_{PDFF}- specific heat of dry fine fuel particles, Lpyr– heat of pyrolysis of fuel and FPPC (j) - content of pyrolysis products of fine dry fuel at cell j. As shown in Table 4, this model uses more input parameters taken from forest fire measurements and so this model is semi-physical in nature (semi-statistical in nature). This model also uses cells (of finite volume) and finite volume method-based heat transfer calculation and arrived at the best fit of fire spread. Drissi proved F19 experiment data and his model output are 100% matching. Diagrams are not presented for simplicity sake. This analytical model of Drissi is more reliable and is the basis for online fire simulator software *github.com*.

Table 4 Fire weather parameters for physical modeling of Mohamed Drissi

Grassland Wildfire Parameters	Symbol	Value
Ratio of surface/volume (m^{-1})	σ_k	12240
Char content / content of gaseous pyrolysis products	ν_{char} / FPCo	0.2/0.8
Specific heat capacity ($J\ K^{-1}\ kg^{-1}$)	Cp,k	1110+3.7T
Stratum height (m)	H	0.51
Density of fuel particle ($kg\ m^{-3}$)	ρ_k	512
Dry load ($kg\ m^{-2}$)	m''_{DFF}	0.313
Volume of solid phase fraction	α_k	0.0012
Initial Moisture content	FMCo	0.058
Pyrolysis temperature (K)	Tpyr	500
Ignition temperature (K)	Tign	500
Critical content of pyrolysis products	FPCcr	0
Radiated Fraction	χ_r	0.35
Heat of combustion ($J\ kg^{-1}$)	Δh_c	15.6×10^6
Mean absorption coefficient of the flame (m^{-1})	k_f	0.4
Residence time of the flame (s)	t_c	5
Fuel bed absorptivity	A	0.9
Flame height (m)	Hf	2.04
Speed of wind (at 2m AGL) ($m\ s^{-1}$)	U	4.83
Relative humidity of the air (%)	RH	20
Cell Diameter (m)	D	2.54
Ambient Temperature (K)	T_∞ or Ta	307

Another physical model was put forth by Brou [4]. In this model, the heat flux q_{ij} emitted by burning cell i (radiation and convection) and is received by the unburned new cell j is

.

$$q_{ij} = \frac{\alpha_{fl}\epsilon_{fl}\sigma T_{fl}^4}{H_j}F_{ij} + 0.25A_{fb}\epsilon_{fb}\sigma T_b^4 e^{-0.25A_{fb}d_{ij}} + \frac{0.565k_{fl}Re_{dij}^{\frac{1}{2}}Pr^{\frac{1}{2}}}{d_{ij}H_j}(T_{fl} - T_j)e^{-\frac{0.3d_{ij}}{L_{fl}}} + \frac{0.911A_{fb}k_b Re_{D_i}^{0.385}Pr^{\frac{1}{3}}}{D_j}(T_b - T_j)e^{-0.25A_{fb}d_{ij}} - \frac{\epsilon_{fb}\sigma T_j^4 - T_\infty^4}{H_j} \quad (9)$$

Where ϵ_{fl} - emissivity of the flame, L_{fl} - length of the flame, α_{fl} – fuel's coefficient of absorption, σ - Stefan–Boltzmann's constant, F_{ij} - radiant factor between the flame of i and cell *j*, ϵ_b - emissivity of the embers, k_b - thermal conductivity of the embers, A_{fb} - specific surface area of the fuel, T_b - temperature of the embers, ϵ_{fb} - emissivity of the fuel layer, d_{ij} – the distance fromn *i* to *j*, *Pr* – Prandtl's No, $diam_j$ - diameter of the fuel placed on cell *j*, T_{fl} – *flame* temperature, Tj - temperature of *j*, and Re-Reynolds number. The two Reynolds' numbers $Re_{d_{ij}}$ and Re_{D_i} are

$$Re_{d_{ij}} = \frac{U_{w_{ij}}d_{ij}}{v_g} \text{ and } Re_{D_i} = \frac{U_{fb}D_i}{v_g} \quad (10)$$

Where U_{wij} - wind in direction i to j that is $U_{wo}Cos\beta$, v_g - kinematic viscosity of air at flame temperature, U_{fb} – speed of wind inside fuel layer that is 1-(φ_j U_{wij}), φ_j – fuel's volume fraction in j, Di - diameter of cell i, total energy q_j is given by

$$q_j = \begin{cases} \rho_j C_{pj} \varphi_j \frac{dT_j^t}{dt}, for\ T_j \neq 373K \\ -\rho_j h_{vap} \varphi_j \frac{dw_j^t}{dt},\ for\ T_j = 373K \end{cases} \tag{11}$$

Where ρ_j - density of fuel particle in cell j, $C_{p,j}$ - specific heat of fuel particle in cell j, h_{vap} -enthaly of vaporization of water at 373K, w_j - mass fraction of water in cell j. According to the energy conservation, q_j - summation of q_i over all buring cells (1-N_{bc}).

Table 5 Parameter values for Brou's calculations (F19)

Parameters	Symbol	Initial input
Fuel's coefficient of absorption	α_{fb}	0.6
temperature of fuel flame (K)	T_{fl}	1083
embers' emissivity	ϵ_b	1
fuel layer's emissivity	ϵ_{fb}	0.6
Thermal conductivity of flame(W m^{-1} K^{-1})	k_{fl}	0.0707
thermal conductivity of embers (W m^{-1} K^{-1})	k_b	0.0454
Temperature of embers (K)	T_b	561

Brou's expectation of F19 Fire test is as per the following. F19 trail used Kangaroo (or themeda) grass with a average surface/volume ration of 12,240m^{-1} and average fuel load of 0.313kg/m^2. The size of the meadow plots is 200m X200m, and the ignition starting is line fire of 175m long X span of 56s in inverse bearings. Others parameters : speed of wind 4.8m.s^{-1}, level of bed 0.51m, mass of water 0.058, fuel thickness 512kg.m−3, heat intensity 1480J.kg−1.K−1, fire length 2.7m, ambient temperature 307K. To acquire the fitting cell size for the modeling a few simulation were completed with cell sizes of 0.5m, 0.75m, 1m, 1.25m, and 1.5m. The anticipated and trial paces of spread are compared. The best expectation is acquired with the 1.5m cell size. Consequently, the size utilized in coming up next is taken as 1.5m. The anticipated and noticed forms are displayed in Figure 5 on occasion 56s, 86s, and 138s. At 86s, the anticipated fire outline is in great concurrence with the noticed fire form, both for the head fire and the contiguous fire. At 56s, the later all fire (toward the path opposite to the breeze) is underrated by our model, however, the head fire (in the breeze bearing) is in great concurrence with the noticed fire form. At 138s, the shift in twist guidance caused a change in the noticed fire form. Because of the absence of data on this shift in course, the typical breeze heading was utilized during the reenactment. In any case, the head fire is somewhat very much anticipated. In Figure 5, The noticed fire shape is given by blue triangle; the consumed fuel is shown in the dark colour, and the thermally degraded fuel is in yellow colour. The fit fuel is green colour. The anticipated fire form is in red colour. Brou demonstrated F19 explore information and his model result are matching great. Likewise, Brown and his associate Adou demonstrated C064 air stream fire try information (on white birch tree) and this model result are matching great (Table 2) [5].

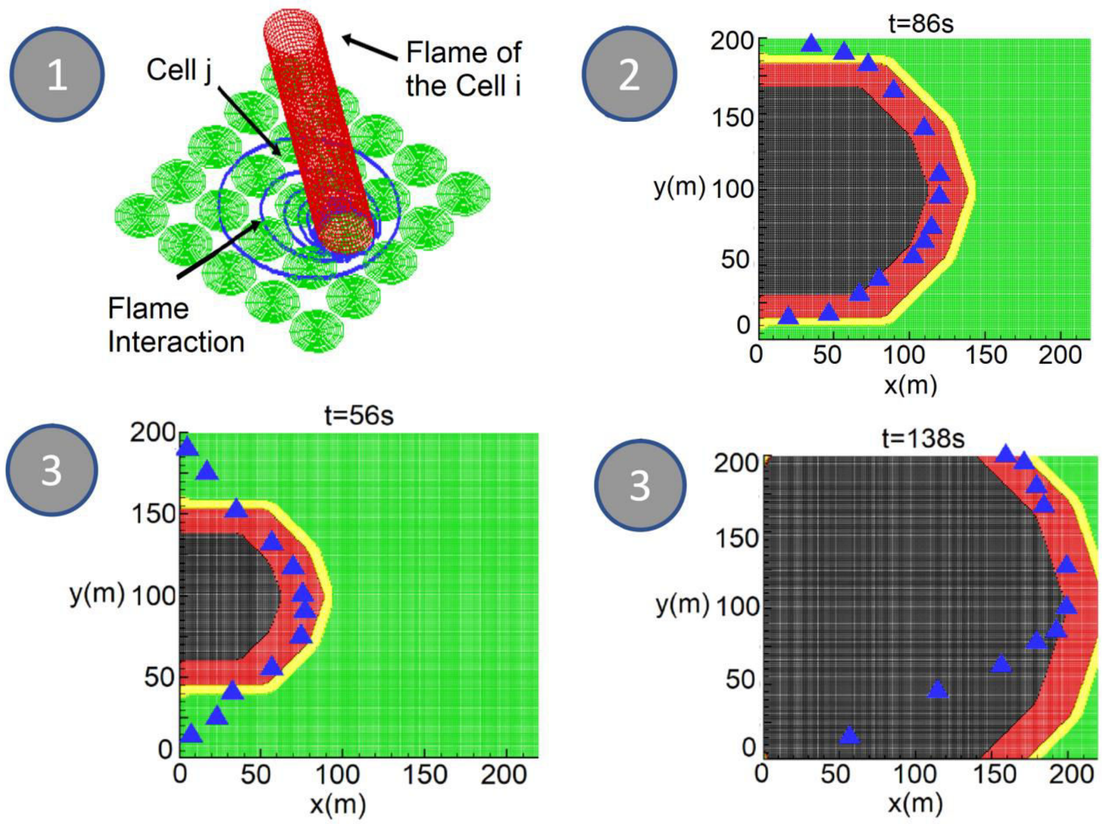

Figure 5 Flame-Fuel Interaction & Rate of Spread

Table 6 Parameter values for Adou's calculations (C064)

Parameters	Initial Values
length of the flame (m)	4
ambient speed of wind (m/s)	4.6
Fuel bed are sloping (°)	0
water mass fraction (initial)	0.063
Fuel bed area thickness (m)	0.21
Ambient surrounding temperature (K)	305
temperature of burning flame (K)	1083

3.4. Modeling for Forestry

Forestry departments or ministries of USA, Canada and well-developed European countries use a model proposed by Dick Rothermel for many dacades in the form of software programs [14]. In this model, fire spread is expressed by Equation 12. Rothermel idea is fire spread by balance due heat of source fire and heat needed to sink fuel.

$$R = \frac{I_R \xi (1+\varphi_w+\varphi_s)}{\rho_b \in Q_{ig}} \qquad (12)$$

In Equation 12, R - fire spread rate, numerator - heat supply source (extending heat flow), denominator - heat sink (heat needed to ignite the fuel). In numerator, $I_R\xi$, - propgating flux in the absence of wind and no slope, I_R -reaction density (rate of energy released per unit area), ξ -flux ratio (fraction of reaction intensity that is heating fuel to ignition), φ_w-wind factor, and φ_s – slope factor. In denominator, ρ_b - bulk density (amount of oven-dry fuel per cubic foot of fuel bed, ϵ - effective heat ratio (ratio of fuel elements heated upto ignition point when combustion starts, and Q_{ig} - preignition heat (heat needed for igniting 1 bound of fuel). Rothermal model is available as software programmes, for USA Forestry. Another significant heat balance based model is by Terry Clark who noticed that fire spread models could be combined with mathematical atmospheric models. This coupling permitted fire to communicate with the air and "make its own weather" in modeling, as it does in reality (Table 7). The barometrical dampness, temperature, wind speed, and wind bearing influence the fire environment, while the smoke, heat motions, and dampness transitions from the fire impact the air. Forest data and fire data are analysed to get better fuel and weather input data. Recently, DeCastro used forest maps provided by satellite using artificial intelligence (machine learning method). Fire propagation model along with machine learning input data gives better estimates for North American Mesoscale (NAM) forestry system [15, 16]. It is pictorially explained using Figure 6. This model is more statistical in nature. As NASA provides easy access to remote-sensing satellites to world, this model is highly reliable and best for forestry and fire control. For example, Figure 7 shows Indian weather maps provided by NASA through its open access FIRMS software (www.earthdata.nasa.gov). In this diagram, Indian map superimposed with fire data of 5th August 2023 is given. Red dots shows hot climate prevailing in Tamil Nadu during the first week of August 2023. In Figure 7, the red and yellow colours that present in the world weather map (detailing 25th April-1st May 2023 fire and heat data) is due to active fires and thermal anomalies. Thermal anomalies are due to wildfire, gas ire and volcano eruption. Thus, modeling forest fires are made easy by statistical models. In addition, this fire data can be feed into analytical models also. However, availability of proper machine learning softwares and supercomputers are required to use MODIS maps for feeding in to fire models. Anyway, forestry's softwares that use forest fire models are not flexible and predictions are very useful to real-time forestry. It is inferred from recent forest fires in Americas and Europe. Even if predictions are in advance, fire control needs firefighting equipment for faster action. For example, copters fitted with fire extinguishers are required to control wildfires. Also, models use old data that are weather data obtained by satellites yesterday or earlier. Weather pattern changes often leading to failure of the model that use previous day or old data. Models needs proper input data. Many models that use less data predict poorly [2, 9, 12, 16].

Table 7 Input and Output Data of Statistical Model

Input		Model							Output
Weather Topography Land Use Soil	→	***Weather Research and Forecasting (WRF) Model***							
		↓	T, RH Rain		Win d	↓↑	Heat Vapor Flux		
Fuel Description Elevation Ignition Time Location	→	***Fuel Moisture Model***		→ ***SFIRE***	***Surface Fire Spread Model*** →			→	Are Burned Heat Flux Flame Intensity Rate of Spread

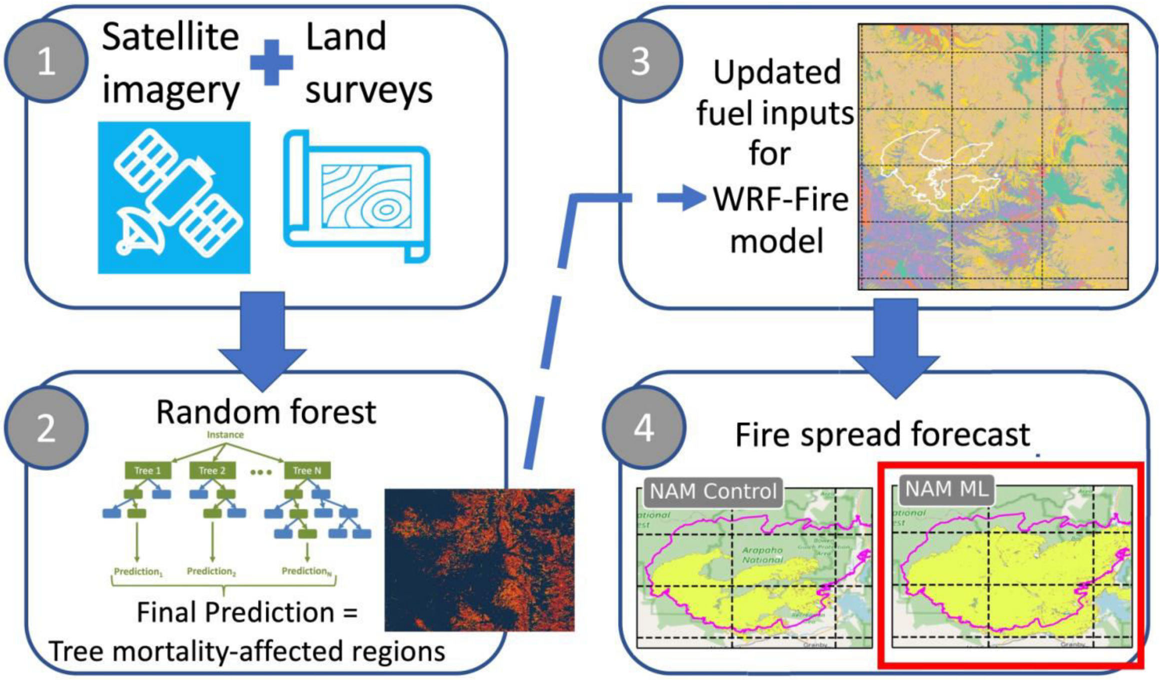

Figure 6 Solver Scheme in Semi-Empirical Models

Figure 7 Active Fire & Thermal Anomalies (MODIS)

4. Conclusions

Empirical models utilizing FWI and FDI may quickly and effectively predict the fire vulnerability. Numerous stochastic techniques and cellular automata are used to model heat propagation caused by the interaction of flame and fuel. MATLAB or Delphi applications can tackle heat transfer model-based fire propagation problems. Many semi-empirical models produce excellent predictions. Heat transfer differential equations of many physical models are resolved using numerical methods or my custom-made computer algorithms. Physical models predicted well the fire behavior of international crown fire modeling experiments. Forestry departments of many developed countries deployed MODIS data and Rothermel model based approaches to wildfire control.

References

1. Yara EzAl Deen Sultan & Kanni Raj Arumugam Pillai, Wild Fires and Climate Change: Health, Air Quality, Wild Fires and Causes in India, *Indonesian Journal of Social and Environmental Issues*, Vol.4, No.1, 2023, pp.72-80
2. Kanni Raj Arumugam Pillai & Yara EzAl Deen Sultan, Wildfire Models – Concise Review, *International Journal of Innovative Research and Technology*, Vol.10, No.3, 2023, pp.161-166
3. Mohamed Drissi, Modelling the spreading of large scale wildland fires, *Proceedings of the large wildland fires conference*, Rocky Mountain Research station, Missoula, USA, 2014, pp.278-285.
4. Akahoua D.V. Brou, Numerical Study of the Effectiveness of a Firebreak in a Savanna Area and the Sizing Rules by an Optimised Fire Propagation Model, *Fire*, Vol.5, No.5, 2022, Article ID – 156
5. J.K.Adou, A.D.V.Brou & B.Porterie, Modelling Wildland fire propagation using semi-physical network model, *Case Studies in Fire Safety*, Vol.4, 2015, pp.11-18
6. Satendra, Ashutosh Dev Kaushik, Forest Fire Disaster Management, *National Institute of Disaster Management*, Ministry of Home & Cooperation, Government of India, New Delhi, India, 2014
7. Anoop Singh, India State of Forest Report, *Forest Survey of India*, Ministry of Environment, Forest & Climate Change, Government of India, New Delhi, India, 2021
8. Pravesh Saklani, Forest Fire Risk Zonation – A Case study in Pauri Garhwal, Uttarakhand, India, International Institute of Geo-information Science and Earth Observation, Enschede, The Netherlands & Indian Institute of Remote sensing, Dehradun, India, M.S.Thesis, 2008
9. Claudia Vitolo, Francesca Di Giuseppe, Christopher Barnard, Ruth Coughlan, Jesus San Miguel Ayanz, Giorgio Libert & Blazej Krzeminski, ERA5-based global meteorological wildfre danger maps, *Scientific Data*, Vol.7, 2020, Article ID – 216
10. Georgios Efstathiou, Savvas Gkantonas, Andrea Giusti, Epaminondas, C.Michael Foale & Rhona R.Foale, Simulation of the December 2021 Marshall fire with a hybrid stochastic Lagrangian-cellular automata model, *Fire Safety Journal*, Vol.138, 2023, Article ID- 103795
11. Epaminondas Mastorakos, Savvas Gkantonas, Georgios Efstathiou & Andrea Giusti, A hybrid stochastic Lagrangian – cellular automata framework for modelling fire propagation in inhomogeneous terrains, *Proceedings of the Combustion Institute*, Vol.39, No.3, 2023, pp.3853-3862
12. Lorenzo Palmieri & Henrik Jeldtoft Jensen, The Forest Fire Model: The Subtleties of Criticality and Scale Invariance, *Frontiers in Physics - Interdisciplinary Physics Section*, Vol.8, 2020, Article ID-257
13. A.M.Grishin & F.A.Albini, Mathematical modeling of forest fires and new methods of fighting them, Publishing House of the Tomsk State University, Tomsk, Russia, 1997
14. Joe H. Scott & Robert E. Burgan, Standard Fire Behavior Fuel Models : A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model, General Technical Report of Forest Srvice, Rocky Mountain Research Station, Fort Collins, Colarado, USA, 2005
15. Yiqing Xu, Dianjing Li, Hao Ma, Rong Lin and Fuquan Zhang ,Modeling Forest Fire Spread Using Machine Learning-Based Cellular Automata in a GIS Environment, *Forests*, Vol.13, 2022, Article ID-1974
16. Amyl L.DeCastro, Tomothy W.Juliano, Branko Kosovic, Hamed Ebrahimian & Jennifer K.Balch, A Computationally Efficient Method for Updating Fuel Inputs for Wildfire Behavior Models Using Sentinel Imagery and Random Forest Classification, *Remote Sensing, Vol.14, No.*6, 2022, Article ID-1447.