Australian Government
Bureau of Meteorology

AFDRS Pine Model

The Pine Model in AFDRS is used for softwood plantations, mainly of pine species, across Australia. Pine plantation fuels cover approx. 2% of Australia.

What is the AFDRS Pine model?

The Pine Plantation Pyrometrics (PPPY) model system was developed in a collaboration between CSIRO, the Canadian forest service, and University of Trás-os-Montes and Alto Douro (UTAD) in Portugal. It aimed to predict the rate of spread and type of fire over the full range of fire behaviour in industrial pine plantations for a variety of fuel complex structures (previous models for pine were specific to the species or location of the plantation).

In contrast with other empirical-based models, this model combines some empirical components with simplified physical descriptions of the heat transferred to unburned fuels. The full PPPY system is very complicated, consisting of over 100 equations, so for computational efficiency a simplified version is used in the AFDRS. This 'light' version replaces some of the semi-physical modelling components with empirical-based equations.

Inputs and outputs

The simplified pine model still requires a significant number of inputs, however the key inputs for this model are 10m open wind speed, temperature, relative humidity, surface fuel load and depth, fuel strata gap (distance between surface fuel layer and bottom of the canopy), and the canopy bulk density.

This model does not have a go/no-go threshold, but it does vary the calculation of Rate of Spread (ROS) based on the parts of the fuel (surface litter and/or canopy) involved in the fire. The surface ROS and intensity is calculated, then the system determines if crowning is likely to occur. If the crowning condition is met, the system then calculates canopy ROS and determines if it will be a passive or active crown fire, refining canopy ROS based on this crown fire state. The calculations made by the model are summarised in the flow diagram on the right.

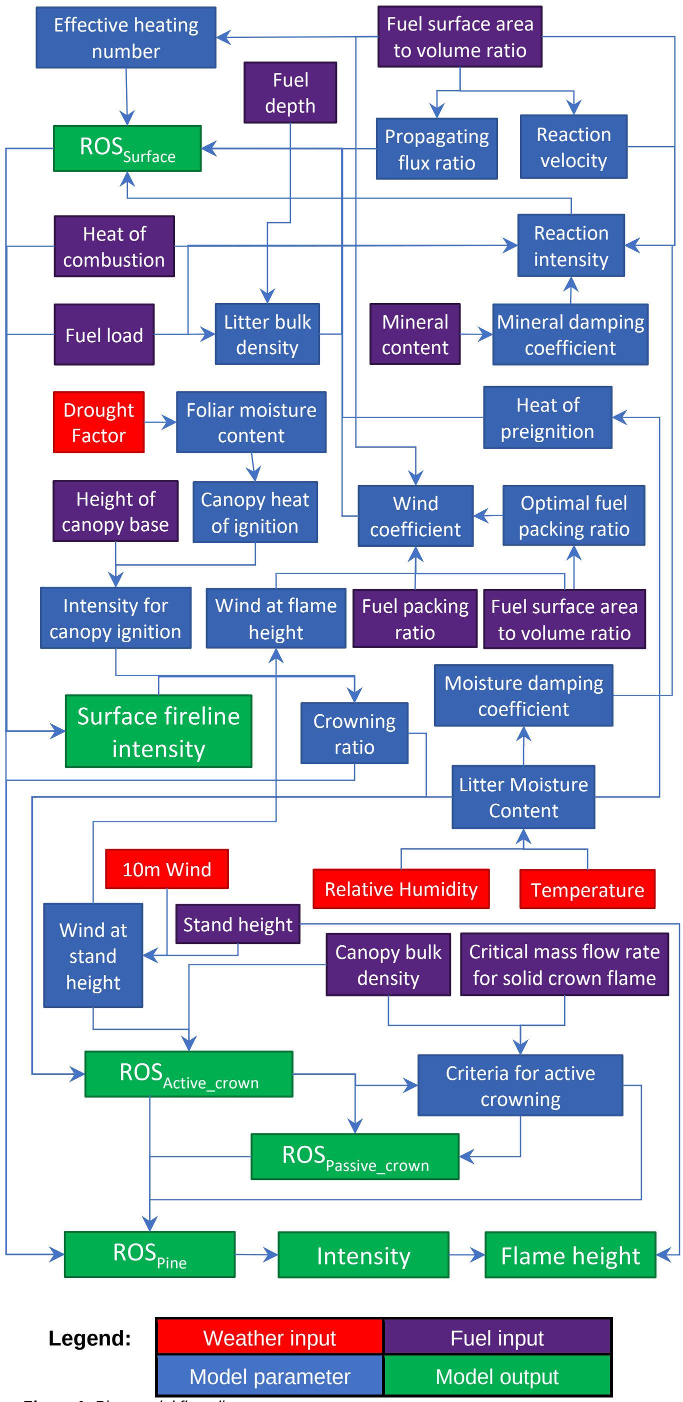

Figure 1: *Pine model flow diagram*

Model equations

The full set of equations for the AFDRS implementation of the PPPY model is quite complicated; a summary of is provided here, and the full set of equations is available in the appendix at the end of this guide.

As with other models, dead fuel moisture content, in this case litter moisture content, is calculated from temperature and relative humidity:

$$MC_{litter} = 4.3426 + 0.1188RH - 0.0211T$$

For stand height, h, we can calculate the wind speed at stand height, U_{SH}, and wind at flame height, U_{FH}. A wind coefficient (to be used in the ROS equation) can then be calculated:

$$C_{wind} = A(54.68 \times U_{FH})^{B}\left(\frac{P}{P_0}\right)^{-E}$$

where A, B, and E, P, and P_0 are functions of fuel parameters.

The surface rate of spread (m/h) is then calculated as:

$$ROS_{Pine\ (S)} = 18.288(1 + C_{wind}) \times f_{Availability}$$

Where $f_{Availability}$ uses the drought index (KBDI/SDI) and McArthur Drought Factor (DF) based on the Vesta Mk2 fuel availability:

$$f_{Availability} = \frac{1.008}{(1+104.9\exp(-0.9306 \times C1 \times DF))}$$

Where C1 is as an adjustment that takes into account Wind Reduction Factor (WRF), restricted to vary between 3 and 5 and KBDI:

$$C1 = 0.1((0.0046WRF^2 - 0.0079WRF - 0.0175)KBDI + (-0.9167WRF^2 + 1.5833\ WRF + 13.5)$$

We define $I_{critial}$ as the intensity of the surface fire required to ignite the canopy and it is a function of Drought Factor and the height of the canopy base above the ground. Surface fireline intensity, I, is calculated using Byram's (1959) equation:

$$I_{surface} = hwROS_{surface}$$

The crowning ratio is then defined as:

$$r_c = \frac{I_{surface}}{I_{critial}}$$

If $r_c > 1$ the fire is likely to spread to the canopy.

Canopy fires in pine plantations can either be active or passive. To determine whether a crown fire will be active or passive, we calculate the Criteria for Active Crowning:

$$CAC = \frac{ROS_{Pine\ (A.C.)}\rho_{canopy}}{60f}$$

Where f and ρ_{canopy} are fuel inputs, and the Rate of Spread for active crown fires in pine is given by:

$$ROS_{Pine\ (A.C.)} = 661.26U_{SH}{}^{0.8966}\rho_{canopy}{}^{0.1901}e^{-0.1714MC_{litter}}$$

When $CAC \geq 1$ the crown fire is likely to be active and we use $ROS_{Pine\ (A.C.)}$ for the rate of spread. Otherwise, for passive crown fires, the rate of spread is given by:

$$ROS_{Pine\ (P.C.)} = ROS_{Pine\ (A.C.)}e^{-CAC}$$

Though passive crown fires tend to spread as a combination of surface and crown fires, so we take the maximum of the two. The ROS (m/h) of fire in Pine plantations can be summarised as:

$$ROS_{Pine} = \begin{cases} ROS_{Pine\ (S)} & r_c \leq 1 \\ max[ROS_{Pine\ (S)}, ROS_{Pine\ (P.C.)}] & r_c > 1, CAC < 1 \\ ROS_{Pine\ (A.C.)} & r_c > 1, CAC \geq 1 \end{cases}$$

Overall/total intensity can then be calculated from Byram's equation:

$$I_{total} = hwROS$$

Where fuel load, w, and rate of spread, ROS, are chosen based on the type of fire occurring (surface, passive crown, or active crown). Note: the canopy fuel load is added if there is crowning, either active or passive.

From this we can find the flame height:

$$F_{height} = 0.07755(I_{total})^{0.46} + \Delta H$$

Where Δ is 1 for active crown fires and 0 otherwise.

Because information about time since harvesting and silvicultural management is not available in the AFDRS, fire behaviour is calculated using an ensemble of 6 different classes of fuel, with individual members first calculated then combined using a weighted mean.

Fuel	Model	Ensemble	Surface load (t/ha)	Canopy load (t/ha)	Canopy base	Canopy bulk density (kg
1	Grass	9.1	-	-	-	-
2	Pine	15.1	4	11.5	0.7	0.17
3	Pine	15.1	5	12	1.5	0.18
4	Pine	12.1	8.5	12	2.5	0.18
5	Pine	9.1	10	8	6	0.12
6	Pine	39.4	7	10	14	0.15

Model behaviour and limitations

The simplification of the model for AFDRS replaces some of the semi-physical modelling with empirical equations for the transition between surface and crown fires, which results in a loss of predictive power. However, at the landscape-scale of AFDRS, it is not a noticeable loss as the input values are already more averaged than what the original PPPY system was designed for.

A standardised description for fuel age and type is used, with fuels assumed to evolve in a certain way through time. Different varieties/species of pine than those used in the model development may develop differently, and the idealisation used in the model does not capture the full variety of surface fuels possible within a pine forest.

The adjustments made to the 10m wind to achieve the stand height and flame height winds are assumed from other research, but they have not been investigated further and it is not clear if they are appropriate for pine plantations. The effect of recent rainfall and its integration into the model through the drought factor is also assumed; the impact of rain on fuel availability is an area that needs further research.

This model assumes the fire has reached a quasi-steady state, so it may overpredict in the initial stages of a fire. It is most sensitive to wind speed and generally has a weak response to changes in fuel moisture content, however it tends to underestimate surface fires burning in marginal conditions, namely $MC_{litter} > 25\%$.

Natural variation in wind speeds can cause a cycling between surface and crown fires, but the model assumes only one mode is present, so when forecast winds speeds are just below the threshold for crown fires the model may underpredict ROS (actual fires may propagate as a combination of both surface & crown fires, and crown fires spread faster).

Fuel sub-types

This model was developed specifically for pine plantations, so it has just the one fuel sub-type.

Pine

All softwood plantations, which in Australia are predominantly *pinus radiata*, have been classified into the pine fuel type.

Figure 2: Fuel structure in radiata plantations. Top: Mature stand after 2nd thinning. Bottom: effect of pruning in reducing vertical fuel continuity. Southeast SA.

Original research paper: Cruz, M.G., Fernandes, P.M., 2008. Development of fuel models for fire behaviour prediction in maritime pine (Pinus pinaster Ait.) stands. International Journal of Wildland Fire 17, 194-204.

FIND OUT MORE

For more information about the Pine Model, contact the **Fire Weather, Heatwave and Air Quality Environmental Prediction Services Team** at **fireweather@bom.gov.au**.

Appendix: full suite of model equations

The dead fuel moisture content (a.k.a. litter moisture content) is calculated using relative humidity and temperature:

$$MC_{litter} = 4.3426 + 0.1188RH - 0.0211T$$

For a given stand height, H, we can calculate the wind speed at stand height from the 10m wind:

$$U_{SH} = U_{10}\frac{ln\left(\frac{0.36H}{0.13H}\right)}{ln\left(\frac{10+0.36H}{0.13H}\right)}$$

From which we can calculate the wind at flame height:

$$U_{FH} = U_{SH}e^{-0.48}$$

We then define the following values:

- $FuelAvailability = 1.008(1 + 104.9e^{-0.9036DF})^{-1}$ where DF is the drought factor.
- $FuelLoad = w \times FuelAvailability$, where w is the surface fuel load.
- Fuel surface area to volume ratio, $\sigma = 1700$ ft^{-1}
- Bulk density, $\rho = \frac{FuelLoad}{FuelDepth}$ where $FuelLoad$ is in lb/ft^2
- Particle density = 32 lb/ft^3
- Fuel packing ratio, $P = \frac{BulkDensity}{ParticleDensity}$
- Optimal fuel packing ratio, $P_0 = 3.348\sigma^{-0.8189}$
- Heat of combustion, $h = 18{,}6800$ kJ/kg
- Propagating flux ratio, $\chi = \frac{e^{0.539352\sqrt{\sigma}}(\sigma+0.1)}{192+0.2595\sigma}$
- Mineral damping coefficient, η_s, for a given mineral content (currently set at 0.01 for effective mineral content and 0.0555 for total mineral content, both used for different things in the model), is: $\eta_s = 0.174(MineralContent)^{-0.19}$
- Moisture damping coefficient, is a cubic of litter moisture content using $x = \frac{MC_{litter}}{30}$: $\eta_m = 1 - 2.59x + 5.11x^2 - 3.52x^3$
- The wind coefficient is $C_{wind} = A(54.68U_{FH})^B\left(\frac{P}{P_0}\right)^{-E}$ where $A = 7.47e^{(-0.133\sigma^{0.55})}$, $B = 0.02562\sigma^{0.54}$, and $E = 0.715e^{-0.000359\sigma}$.
- Maximum reaction velocity, $\gamma_{max} = \sigma^{1.5}(495 + 0.0594\sigma^{1.5})^{-1}$
- Optimum reaction velocity $\gamma = \gamma_{max}\left(\frac{P}{P_0}\right)^{\alpha} e^{\alpha\left(1-\frac{P}{P_0}\right)}$ where $\alpha = (4.77\sigma^{0.1} - 7.27)^{-1}$
- $NetFuelLoad = \frac{FuelLoad}{1+MineralContent}$ where $MineralContent = 0.0555$
- Heat of preignition, $h_p = 250 + 11.16MC_{litter}$
- Reaction intensity, $R = \gamma \times NetFuelLoad \times HeatOfCombustion \times \eta_s \times \eta_m$ where $HeatOfCombustion = 8000$ Btu/lb
- Effective heating number, $N_h = e^{-138\sigma^{-1}}$
- ρ_{canopy} is the canopy fuel bulk density
- f is the critical mass flow rate, currently estimated at 3.0 kgm^{-2}min^{-1}

The surface rate of spread (m/h) is then calculated as:

$$ROS_{Pine\ (S)} = 18.288\frac{R\chi(1 + C_{wind})}{\rho N_h h_p}$$

Foliar moisture content, $MC_{foliar} = 150 - 5DF$, is used to define the canopy heat of ignition, $h_i = 460 + 26MC_{foliar}$. The intensity of the surface fire that is required to ignite the crown/canopy is then calculated: $I_{critical} = (0.1H_{cb}h_i)^{1.5}$ where H_{cb} is the height of the canopy base above the ground (m). Surface fireline intensity is calculated using the same equation as other models: $I_{surface} = hwROS_{surface}$. We then use these intensity values to define the crowning ratio: $r_c = \frac{I_{surface}}{I_{critial}}$

If $r_c > 1$, the fire is likely to spread to the canopy (and conversely, if $r_c \leq 1$ the fire is unlikely to crown). Canopy fires in pine plantations can either be active or passive. To determine whether a crown fire will be active or passive, we first need to determine the Rate of Spread assuming active crowning:

$$ROS_{Pine(A.C.)} = 661.26U_{SH}{}^{0.8966}\rho_{canopy}{}^{0.1901}e^{-0.1714MC_{litter}}$$

We then calculate the Criteria for Active Crowning:

$$CAC = \frac{ROS_{Pine(A.C.)}\rho_{canopy}}{60f}$$

When $CAC \geq 1$ the crown fire is likely to be active and we use $ROS_{Pine\ (A.C.)}$ for the rate of spread. For $CAC < 1$ we expect a passive crown fire, and the Rate of Spread is:

$$ROS_{Pine\ (P.C.)} = ROS_{Pine\ (A.C.)}e^{-CAC}$$

Passive crown fires tend to spread as a combination of surface and crown fires, so we take the maximum of the two. The ROS (m/h) of fire in Pine plantations can now be summarised as:

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Overall/total intensity can then be calculated from Byram's equation, $I_{total} = hwROS$, where w is surface fuel load and/or canopy load, chosen (along with ROS) based on the type of fire occurring (surface, passive crown, or active crown).

From this we can find the flame height:

$$F_{height} = 0.07755(I_{total})^{0.46} + \Delta H$$

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