Effect of FMC on flammability of forest fuels

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Australian bushfire researchers have commonly used FMC of eucalypt litter bed as an input variable for fuel bed flammability and ROS as a quantitative output indicator, but the range of correlations they have used has been too large for scientifically credibility. The correlations between FMC and ROS have varied from FMC to the power 0.8 to more than 2.5, yet contemporaneous international studies are consistently around the power 1. Despite the wide variation, there has been a dearth of systematic analysis. One of the few studies returned a power exponent of 0.8 to 1, but this has been disregarded in favour of unsupported higher exponents. This note attempts to quantify the impact of FMC of forest fuel flammability using a first principles' approach. It firstly explores what theory says the effect of FMC should be on fuel bed flammability, and tries to quantify it. It then compares this finding to studies in litter bed and elevated fuels and finally compares these findings to Australian levels and discusses the implications when applied.

This paper is one of the Back to Basics series:
Some core underpinning theory is incorporated into the first Paper:
1 Manual of bushfire behaviour mechanisms in Australian vegetation
Some more basic theory about spot fire behaviour introduces the second paper:
2 Spot fire direction and spread in severe bushfire attack - Australian vegetation
Together they provide a useful scientific background for the following papers:
3 Flame spread and flame height in eucalypt forests and grassland in severe bushfire
4 How the East Kilmore Black Saturday fire got away
The foregoing papers become the basis for analysing the findings in major research works on bushfire behaviour in Australian forests:
5 Back to basics approach for bushfire behaviour research
6 Usable findings in major bushfire behaviour research in eucalypt forests – McArthur, Burrows, Vesta
The wide range of published correlations between FMC and ROS led to the next paper, which takes a back to basics approach to FMC and flammability
7 Effect of FMC on flammability of forest fuels

Theory

At its basic level, a line of flame burns and progresses through a fuel bed by igniting adjacent unburnt fuel. Intuitively, a bone dry fuel bed will be more flammable that say one at 12% FMC, and will therefore ignite faster, produce a taller flame and run faster at a given wind speed. Madrigal et al (2009) quote Anderson's 1970 framework for understanding flammability, and this paper now focuses on the two most relevant components for flame spread - ignitability and combustibility, which Madrigal et al measure as time to ignition and peak mass loss rate (MLR) respectively.

When heat is applied to a fuel particle, it has two innate thermal properties that determine ignition rate and combustion rate – specific heat capacity and thermal conductivity. They also act together to influence the pyrolysis rate (Spearpoint and Quintiere, 2000) which determines the supply rate of volatile gases, measureable in forest fire behaviour as peak mass loss rate (MLR). This section firstly examines specific heat capacity (Cp) and thermal conductivity (k) and then peak MLR.

The Thomas (1970) approach is helpful in explaining the impact of Cp and k. Flame spreads when the adjacent unburnt fuel bed is raised to ignition temperature (defined as 300^0C above ambient). Thomas identifies an indicator heat of combustion, Delta H = the heat required to raise 1 kg of fuel to ignition **Delta H = Cp x delta T**

(1) Heat capacity is the energy (kJ) absorbed by wood fuel to raise 1kg by 1 degree C.
The Wood Handbook (2010) formula is **Cp = 0.0038 x T + 0.1** Where T is K^0.

Using Cp at ambient (300^0K) of 1.3 kJ / kg / degree K, which can be used as a proxy for bone dry litter bed fuel (dead fine woody material).
Therefore ***Delta H = 1.3 x 300 = 390 kJ / kg***
If this fuel is engulfed by flame, the equivalent heat flux is 40 kW / sq m, which is calculated as follows:
Heat flux = Hig x delta T,
Where Hig = convection heat transfer coefficient for engulfing flame = 0.05 $kW/m^2/K^0$ (SPFE Handbook, 2015) and delta T = 800C (assuming flame is 800^0C above ambient)
Therefore the indicative time to ignite 1 kg of fuel = 390 / 40 = 9.75 sec.

What is the effect on time to ignition of higher moisture content (say 12%)?
Cp water = 4.18 kJ/kg/deg. The Wood Handbook (2010) equation for Cp variation with FMC as follows:
Cp_{wet} for FMC% = [Cp_{dry} + (FMC% x 4.182)] / (1+FMC%)

Therefore **Cp = [1.3 + (0.12 x 4.18)] / 1.12 = 1.6 kJ / kg / deg**
This is a 23% increase. The Wood Handbook also includes an adjustment for the water to cellulose bonds, and lists the 12% FMC Cp as 1.7 kJ / kg / deg. Therefore **Delta H = 1.7 x 300 = 510 kJ / kg**

Additional heat is required to vaporise the moisture within the fuel from ambient to boiling point (say 100 – 30 = 70^0C)., heat of vapourisation of water at 100^0C = 2257 kJ / kg.
Hv = 12% x (4.18 x 70 + 2257) = 314 kJ / kg.
Therefore, total heat required = 510 + 314 = 824 kJ / kg
Therefore, increasing FMC from zero to 12% causes time to ignition to approximately double to 824/40 = 20.6 sec.
Alternatively expressed, for every 12% reduction in FMC, time to ignition halves, and for every 6% reduction in FMC, time to ignition reduces by approx 25%.

Thus, when dead fuel in a fuel bed is under flame impingement, the influence of changing FMC on time to ignition is linear and minor.

(2) Thermal conductivity measures the rate of heat flow through the fuel particle.
Thermal conductivity across the grain = k = ρ x (0.194 + 0.0041 FMC%) + 0.018
Where ρ = density of fuel particle

Thermal conductivity for Douglas fir is 0.12 W / m (depth) / degree K when bone dry and increases to 0.14 at 12% FMC.

To heat a sq m of 2mm thick bone dry fuel to ignition (delta T = 300^0C) requires 7.2 kW / sq m = 7.2 kJ / sq m per sec.
To heat 1 sq m of 2mm thick fuel of 12% FMC by 300C requires 8.4 kW / sq m.
When the impinging flame is 40 kW / sq m, the change in rate of heat penetration is marginal.

Thus, when dead fuel in a fuel bed is under flame impingement, the influence of increasing FMC to 12% on rate of heat conduction is linear and minor.

Summary so far The impact of changing FMC on two core thermal properties of dead fuel in a fuel bed is linear and minor.

(3) Peak MLR
A significant influence of minor to moderate FMC increase is to reduce peak MLR but, at high moisture levels, peak MLR can be increased due to water vapour loss and peak MLR of volatiles can be delayed, compared to dry fuels.
This Benkoussas et al (2007) MLR chart indicates the succession and the overlap of vapour loss, wood pyrolysis and char pyrolysis / oxidation periods in very thin fuel particles (0.5mm diameter at 30% FMC) subject to 40 kW / sq m irradiation.

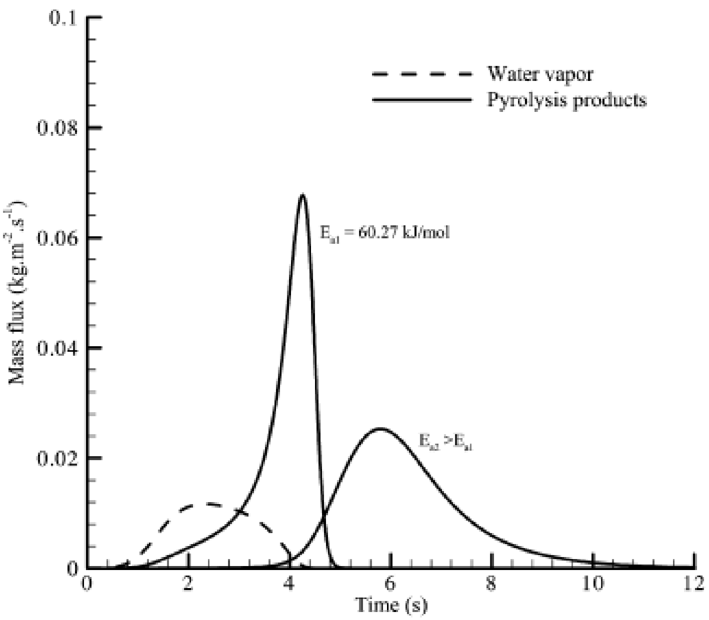
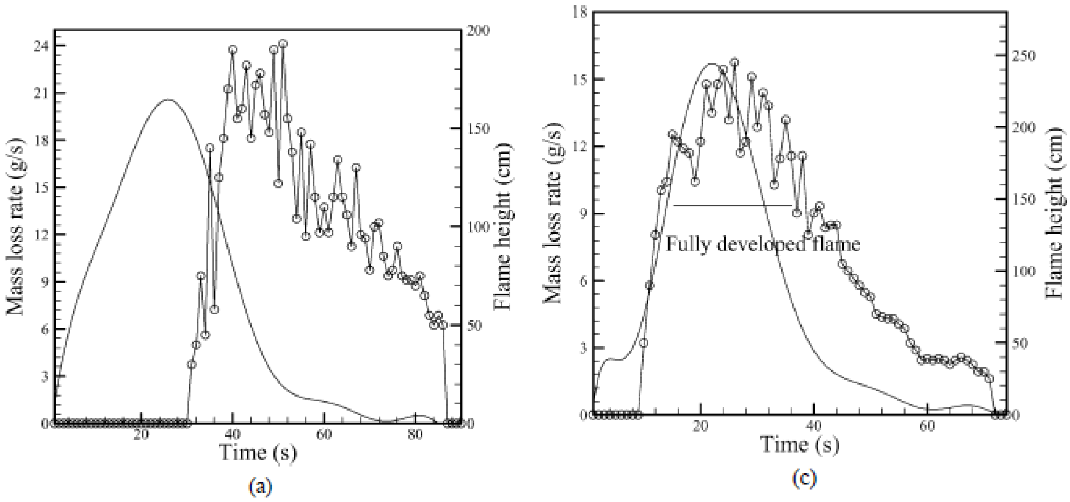


Figure 1 Successive flow rate curves of water vapour, pyrolysis volatiles and char losses in 0.5 mm diameter sphere at 30% FMC under radiant heat of 40 kW / sq m. Copy of Fig 1 (Benkoussas et al, 2007).

The delaying impact on FMC in a fuel bed has been confirmed by Sun et al (2006) who burnt baskets of chaparral foliage ranging from dead (9% FMC) to fresh (90% FMC), lit from below by flame impingement. They found that peak MLR in dry fuel beds coincided with time of peak flame height, but peak flame height was delayed significantly after peak MLR in high FMC (> 40%) fuel beds (delay in sec = 0.4 (FMC – 40)). They confirmed the delay was due to initial vapourisation of moisture. Once moisture was expelled, peak flame height in all fuel beds had the same correlation with relevant maximum MLR to the power 0.4.



Live chamise foliage 95% FMC Dead chamise foliage 9% FMC

Figure 2 Successive flow rate curves of water vapour, pyrolysis volatiles and char losses in 0.5 mm diameter sphere at 30% FMC under radiant heat of 40 kW / sq m. Copy of Figure 5 (Sun et al, 2006)

The Sun et al (2006) study demonstrates the influence of FMC on two flammability components - ignitability (= time to ignition) and combustibility (peak MLR) and shows that the close connection between flame height and peak MLR confirms it as a visible indicator of flammability.

Peak MLR influences flame spread rate when ROS is influenced by flame height, as occurs in wind-aided flame spread along a fuel surface (Cleary, 1992). In this case, flame spread occurs in the direction of flow of the hot fire gases and flames. Un-burned material ahead of the pyrolyses front is heated by the flames which are swept ahead by the induced buoyant flow or forced flow.
Wind-aided flame spread rate can be expressed as **ROS = (Fs – Pp) /** $\mathbf{t_{ig}}$
Where Fs is the furthest visible flame tip stretch position along the surface (it represents the length of surface fuel exposed to a significant flame heat flux), Pp is the pyrolysis front position and t_{ig} is the ignition time.
Fs is a function of the heat release rate
Wind aided flame spread is difficult to measure because the flame ahead of the pyrolysis front obscures the front's position.

To summarise: When heated, the mass lost from a bone dry fuel bed is the volatile gases. When heated, total mass lost from a moist fuel bed can be greater because it comprises both volatile gases and non volatile water vapour. Water vapourises earlier than pyrolysis commences. When vapourisation exhausts, MLR becomes fully volatile, and flammability resumes. Flame height and flame rate correspond with the highest MLR at that time.

Research findings

Solid wood fuel
Tran (1992) measured the influence of FMC on average HRR, which is related to MLR by the equation **HRR = Heat of combustion x MLR**. He examined oven dry and 9% FMC wood samples under 50 kW / sq m radiation and deduced a linear but

minor reduction in the 60 second test of 20% (14 ➔ 34%) for hardwood and 27% (9 ➔ 36%) for softwood according this multiplier **(1 - 0.025 x FMC % change)** Thus each 1% FMC change causes an inverse 2 - 3% change to MLR.

This finding supports the theory that FMC change causes an inverse linear but minor change in average MLR. Although average MLR is not usually correlated with peak MLR, the changes are proportionately comparable.

Thin fuel particles

Benkoussas et al (2007, Fig 4) investigated the effect of FMC variation in thin cylindrical fuel particles of varying diameters on the time to reach pyrolysis (they use pyrolysis temperature of 500 K). It can be assumed that time to pyrolysis is closely related to time to ignition.

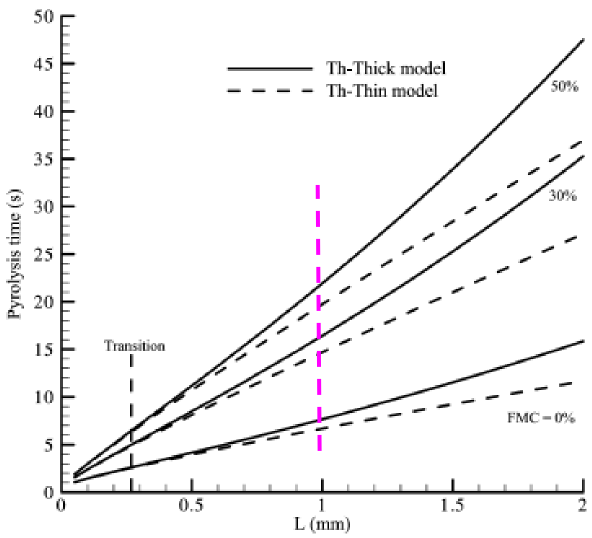


Figure 3 Copy of Figure 4 Benkoussas et al, 2007

Figure 3 shows they found the rate of change is very close to linear. For example, for a given diameter, say 1mm, when FMC increases from 0 to 30%, pyrolysis time increases from 8 to 17 sec (= 9 sec per 30% = 1 sec per 3.3% FMC) and 17 to 23 = 6 sec per 20% (= 1 sec per 3.3% FMC). The scale of change is minor – Increasing FMC from bone dry to 9% or 12% causes ignition time to increase by from 8 to 11 sec or from 8 to 12 sec, = 37 to 50% respectively.

This finding supports the theory that FMC change causes an inverse linear but minor change in time to ignition of a fine fuel particle.

Fuel bed trials

Litter in basket

Madrigal et al (2009) measured combustibility of the test sample by peak MLR - P pinaster pine needles (1.5 kg/sq m) at FMC 9% to bone dry (0%) under 50 kW / sq m radiation. They found peak MLR increased from 0.16 kg / sq m / sec to 0.14 kg / sq m / sec as FMC decreased from 9 to 0%. This is an increase of 14% in MLR. They found that peak MLR was unchanged for the lower fuel loading (0.8 kg / sq m), remaining at 0.14 kg / sq m / sec.

This finding supports the theory that that FMC change causes an inverse linear but minor change in MLR in a fuel bed.

Eucalypt litter beds

Burrows' (1999) laboratory trials provides rate of spread data for three wind speeds and fuel moisture contents between 3% and 10%. He finds for a given wind speed that rate of spread is inversely proportional to FMC. The best correlations are linear to almost linear.. His highest level correlation had the function (***exp (-0.11 x FMC)***, which is identical to the grass FMC function for grass in Cruz et al (2015). This approximates to FMC to power -0.64. It means that for a given wind speed, ROS increases by 60% as FMC decreases from 7% to 3%. This is vastly different from McArthur's (1967) power function (- 2 to 2.5) that quadruples ROS from 7% to 3% FMC.

This finding supports the theory that FMC change causes an inverse (almost) linear but minor change in ROS in a fuel bed.

Non eucalypt litter beds

Rothermel and Anderson (1966) data on Figure 4 shows that for each increasing wind speed curve, ROS increases variably from 9.5% to 4.5% FMC - by 86%, by 33% and by 20% respectively. The highest wind speed increases by 22% from 7.5 to 4.5% FMC.

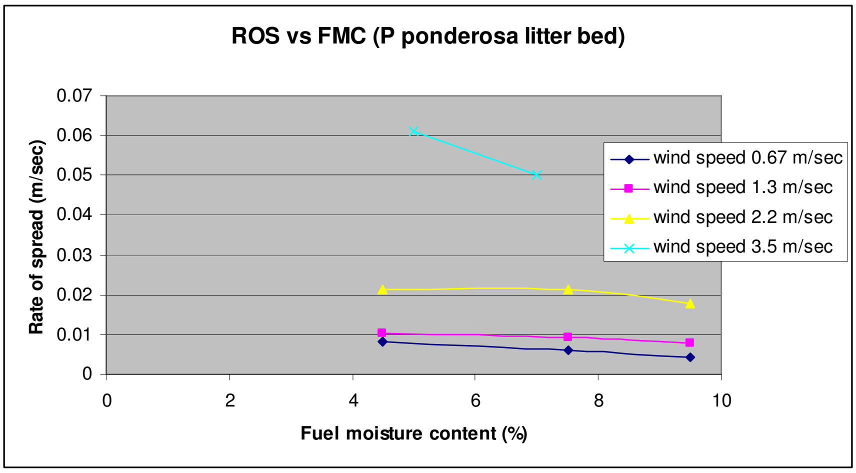
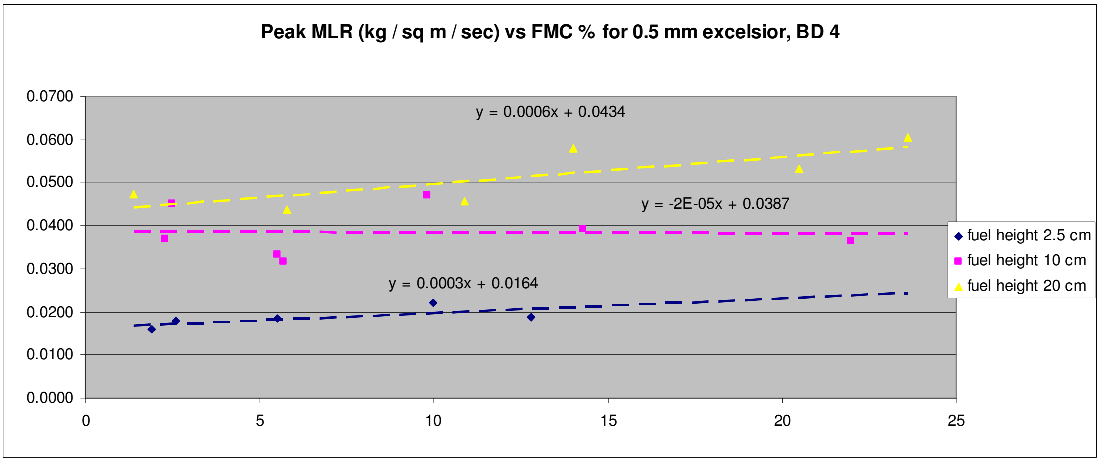


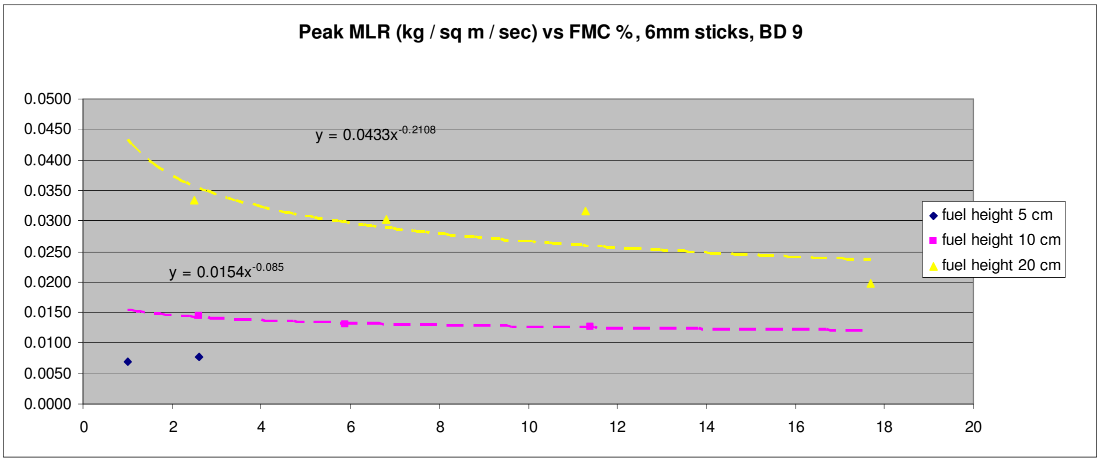
Figure 4 ROS data from Rothermel and Anderson (1966)

This finding supports the theory that FMC change causes an inverse (almost) linear but minor change in ROS in a fuel bed.

Wilson (1982) data in fuel beds of very fine 0.5mm excelsior and 6mm stick was collected in zero wind. Figures WW a and b show the effect of changing FMC on peak MLR was variable but minor for each fuel type and sometimes negligible. Figure 5 shows that flame height tends to reduce as FMC increases.

These findings support the theory that FMC change causes an inverse but minor change and sometimes negligible change in peak MLR of a fuel bed. They also support an inverse but minor change in general flammability, as indicated by flame height reduction as FMC increases.





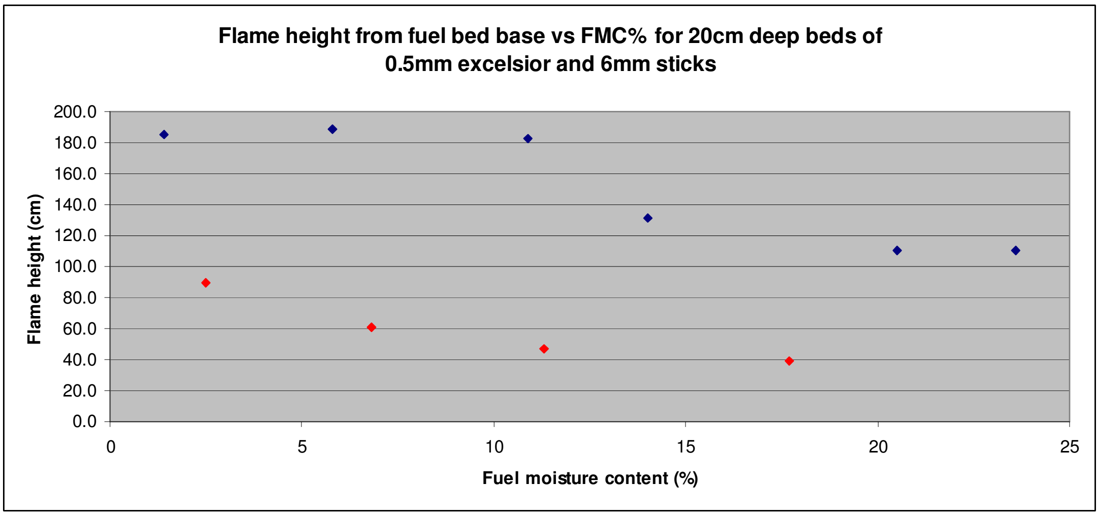


Figure 5 Analysis of Wilson (1982) data showing correlations between FMC and peak MLR and flame height

Elevated fuel beds

Baker (2011) quotes Babrauskas' empirical correlation between FMC of the needles of Douglas fir Christmas trees and peak HRR (heat release rate) which can be presented as follows:

Peak HRR per kg of initial fuel load = 343.8 exp (-0.017 x FMC%)

On average mass lost was 45% of initial mass, and most of that was needles. The correlation is shown on Figure 6 as a slight inverse slope.

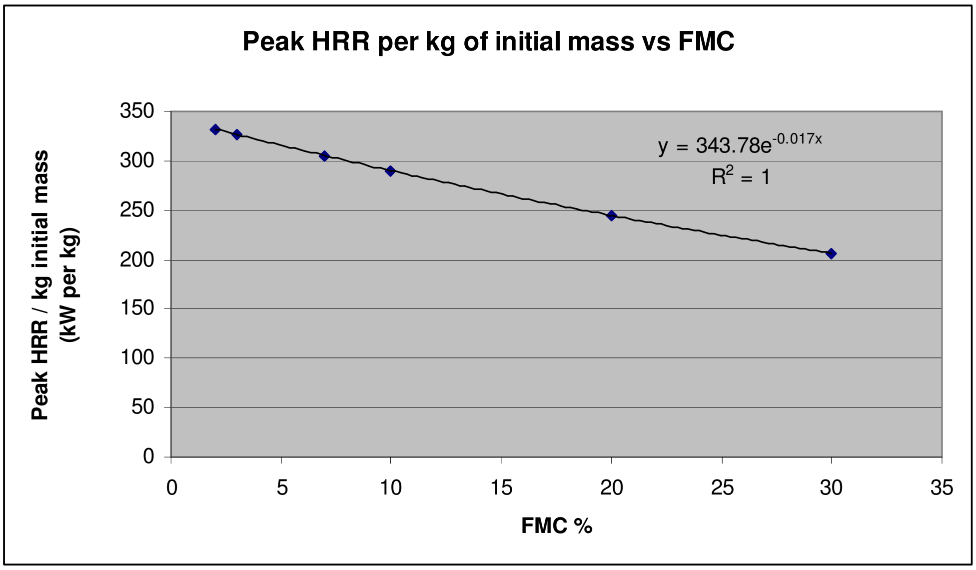


Figure 6 Plot of Babrauskas' empirical correlation between FMC of the needles of Douglas fir Christmas trees and peak HRR

HRR is related to MLR by the equation **HRR = Heat of combustion x MLR.** Figure 7 shows that flame height is positively correlated to peak MLR. This chart therefore links flame height inversely to change in FMC.

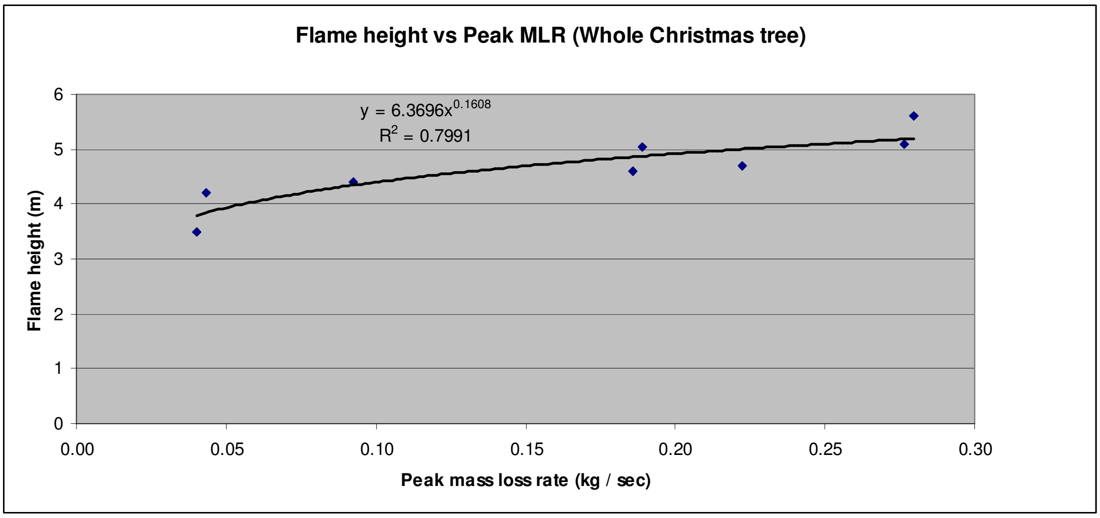


Figure 7 Chart of Baker(2011) data showing the correlation between flame height and peak MLR of whole Christmas trees.

These findings support the theory that FMC change causes an inverse but minor change in peak MLR of an elevated fuel bed. Because of the direct correlation between peak MLR and peak flame height, they also support an inverse but minor change in general flammability, because a decrease in peak MLR causes a lower flame height.

Discussion

The combination of theory and results of systematic FMC studies lead to an inevitable conclusion that change in the lowest 10% range of FMC, eg, 12% to 3%, causes an inverse linear but minor change in flammability level, as measured by peak MLR, an indicator of combustibility. This modest change in theoretical flammability is supported by modest changes in flame height and ROS in systematic studies of fuel beds. The choice of moderate correlation between FMC and ROS is reported for some ROS models, notably Grass fire Meter, mallee heath and button grass heath (Cruz et al, 2015).

This moderate correlation is in stark contrast to the correlations applied in models for eucalypt forest. McArthur (1967) produced a Meter predictor to the inverse power 2 – 2.5. He explained the booster factor was to account for short distance spotting. Project Vesta (2007) generated a model that used the power function – 1.49, adopted from Burrows' field findings, but did not test it. They used it to normalise their data to 7% FMC, and then extrapolated their ROS data to 3% using power -1,49. This multiplied 7% data by 350%, when the moderate correlation would increase it by up to 150%.

The implications are that their model predicts without conforming to scientific validity or theoretical accuracy. The fact that it seriously over predicts ROS for low FMC is not a built in safety factor for a severe bushfire danger day operational advantage, but simply an erroneous prediction.

In science, accuracy and foundational integrity is critical for advancement of scientific knowledge and reliability in application. The Vesta model and to a lesser extent McArthur model have compromised these values and if they are not identified, they cannot be rectified, and until they are rectified, advancement in bushfire behaviour knowledge will be delayed.

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