Predicting Ignition Thresholds in Litter Layers

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Abstract: Knowing when fires can be ignited, and when they cannot, is important for bushfire behaviour modelling and is particularly useful for those working with prescribed fire. Ignition thresholds in litter layers from ten species have been studied in a series of laboratory experiments. Fuel moisture content was used as the primary predictor variable. Litter beds were prepared at a range of fuel moisture contents and ignited at a point with five different methods. Successful ignitions were defined as those that started a fire that traveled 125 millimetres from the ignition point. The probability of ignition success for each species was determined from repeated ignition attempts at specific fuel moisture contents. All ignition datasets were modelled using logistic regression, and the moisture content at which ignition probability was 50% were used to compare them. Ignition thresholds for different litter types ranged markedly and were related to the litter bed density with well aerated fuels igniting at much higher moisture contents than densely packed fuels. The effect of wind was also measured and was found to decrease the fuel moisture content at which fires would ignite when point ignition sources were placed on top of the fuel bed. Ignition thresholds were also found to be sensitive to the pilot ignition source, with the threshold increasing with the ignition source size. The results from these experiments will be used to add lower limits to fire behaviour models and aid the planning of prescribed burning in heathland vegetation.

Keywords: Ignition; Litter; Bushfire; Fuel moisture content

1. INTRODUCTION

The aim of this paper is to define the conditions when fires can be ignited in litter from a variety of species, and to test the effect of ignition size and applying a wind source. This has been done using results from over seven hundred individual ignition attempts made in ten different litter types in a laboratory. Fuel moisture content was used as the main predictor variable throughout these experiments because it has a major effect on fuel ignitibility, is easily altered and can be accurately measured.

This work is still in progress and is part of a project investigating ignition thresholds and initial fire development in heathland fuels. Further sections of the project will investigate ignition and vertical fire development in shrub fuels. Ignition probability models produced from this project will be useful in the planning of prescribed fire and could be added to fire models so that they will only predict fire behaviour when fires will ignite.

2. GENERAL METHODS

The litter ignition experiments were conducted in the laboratory, where fuel and environmental conditions could be controlled. Litter beds were prepared at a range of moisture contents, so that the effect of fuel moisture content on litter ignition could be investigated. Litter from *Allocasuarina nana*, the dwarf she oak, was selected as the standard type and was used for defining an ignition success protocol, testing for differences resulting from different pilot ignition sources, and testing the effect of wind. Litter from nine other species was also used in the investigation of the effect of litter type. All litter beds were prepared in a tray designed to simulate field conditions. The burning area of the tray has a diameter of 250 millimetres and a depth of 18 millimetres. Effort was made to keep litter density uniform for each species, though this is dependant on the variability of particle size. Ignition attempts were repeated between 5 and 10 times at each fuel moisture content depending on variation in fire behaviour. The repeats were used to calculate the proportion of ignition success within each moisture content series.

2.1 Modelling

All of the ignition probabilities were modelled using logistic regression. Logistic regression was selected because the distribution of the data is binomial, with each individual ignition classed as being either successful or unsuccessful. The underlying model used was of the form:

$$\ln\left(\frac{p}{1-p}\right) = a + bm,$$

where p is the probability of ignition, m is the fuel moisture content and a and b are constants. For comparison between data sets the moisture content at which 50% of ignitions succeed, referred to as the m_{50} [Blackmarr, 1972] is used. This provides a good statistic for ignition thresholds due to fuel moisture content.

2.2 Defining Ignition Success

The method selected for defining ignition probability in these experiments is the probability of fire reaching the edge of the tray from the central ignition point. This definition requires a resulting litter fire to travel a distance of 125 millimetres from the ignition point, which necessitates enough fire development to demonstrate fire sustainability. The method most often described in the literature [Anderson, 1970; Blackmarr, 1972] claims successful ignition to have occurred if flaming combustion is evident after the pilot source has gone out. This method was found to be unacceptable, as many unsustainable ignitions would have been categorised as successful. Other definitions were also tried, but the one selected was found to be the most consistent and was simple to measure. The selected method would need to be scaled up for use with large ignition sources.

3. IGNITION SUCCESS FROM DIFFERENT SOURCES

Due to the scale of the experiments, ignition sources were limited to point sources. Three different ignition techniques were used in the project. They were air incendiaries, cotton balls with methylated spirits applied to them, and 1 ml of methylated spirits applied directly to the fuel bed. Further research investigating the effect of larger ignition sources, such as drip torches, is required, but can only be investigated in the field.

Aerial incendiaries are capsules containing potassium permanganate, which are injected with ethylene glycol, causing a delayed flaming reaction. They are used to ignite prescribed fires in remote areas, where they are dropped on site from an aircraft. Aerial incendiaries were to be used as the standard ignition source, but since they produce toxic fumes as the plastic capsule burns, their use was limited in the laboratory. Cotton balls with methylated spirits applied to them were used because they are safe, clean and appropriate for simulating ignition from aerial incendiaries, as they both ignite from the top of the fuel bed. Cotton balls with 1 millilitre of methylated spirits applied were used as the standard ignition source in all of the experiments, as they are an appropriate size for the experiments. The effect of ignition source size on litter ignition thresholds was investigated using cotton balls with 0.5 and 2 millilitres of methylated spirits applied, which were used to ignite the standard litter fuel. Another series of experiments used 1ml of methylated spirits soaked into the litter without a cotton ball. All of these methods were applied to the standard litter bed for comparison.

The results of ignition success from the different pilot sources used are illustrated in Figure 1. The logistic regression curves in Figure 1 were fitted to the individual data sets for each ignition type. The effect of ignition source size can be seen when comparing the ignition sources consisting of methylated spirits applied to cotton balls. The m_{50} increases with the amount of methylated spirits in the cotton ball incendiary. This is because large pilot ignition sources have a better chance of raising the fuel temperature to the heat of preignition than smaller sources [Schroeder, 1969], hence leading to ignition success at higher moisture contents. Blackmarr [1972] also found m_{50} to increase with ignition source size.

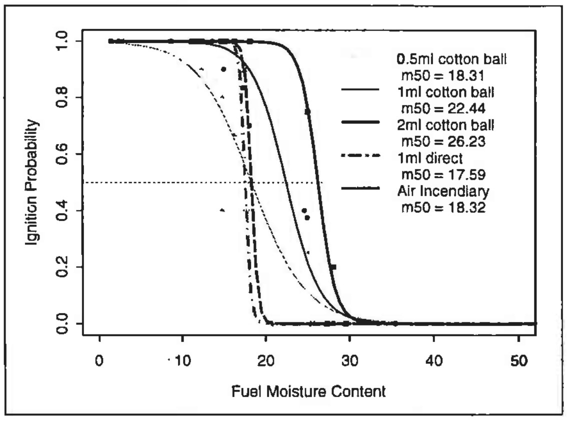

Figure 1. Ignition success with different pilot ignition sources.

The air incendiary and direct application ignition techniques have low m_{50}'s. The relatively low m_{50} from air incendiaries is probably due to of the insulating molten layer of plastic that tends to form underneath the burning parts limiting heat transfer on the litter bed below, causing this source to be ineffective at higher moisture contents. The low m_{50} from direct application of methylated spirits into the litter is due to the fact that fires from direct application ignition burn deeper in the fuel layer. Resulting fires from direct application are more susceptible to the slowing effects of high fuel moisture and subsequently do not reach the edge of the tray.

The slopes of the logistic regression curves in Figure 1 are variable and were found to be related to the flaming times of the pilot ignition technique. The ignition sources with the steepest curves have the longest flaming times. Sources with long flaming times cause a greater proportion of litter close to the ignition point to ignite, subsequently leading to fire spreading to the edge of the tray.

4. WIND INFLUENCE ON IGNITION SUCCESS

The effect of wind was investigated by comparing a set of data collected without wind to one collected when a wind source was applied. Only presence or absence of wind was tested, as there was not enough time available to investigate varying wind velocity. Wind was generated using a domestic fan with a series of grills and mesh filters attached to even the distribution of the flow across the litter tray. The velocity over the tray was 0.5 metres per second.

The effect of presence and absence of wind is presented in Figure 2. Ignition attempts made without wind succeed in conditions when those made in the presence of wind will not. This is because wind decreases heat transfer from the pilot to adjacent litter, making it less likely for the litter to reach ignition temperature. There is no increase in flame contact as the ignition source is located on top of the litter bed. If the pilot ignition source were located within the fuel bed, as is the case with the direct application of methylated spirits, then the flame contact would be increased and the lessening of heat transfer would be less effective. Experiments investigating the effect of wind on ignition from direct application of liquid fuel are currently being conducted.

Ignitions in the presence of wind either resulted in fire reaching all of the way to the edge, or not igniting the litter at all. In comparison ignitions without wind in marginal conditions often resulted in fires that did not reach the edge of the tray, but that did burn a significant proportion of the litter area. Fuel consumption was significantly less in the presence of wind. This is because wind aided fires had shorter flame residence times and only burnt the top of the litter. The effect of wind on other litter types and with similar pilot ignition sources would be expected to show a similar trend. Although the effect of wind speed has not been investigated here, it would be expected that increasing wind speed would decrease the m_{50} with this ignition source. Verification of this would require extensive experimentation.

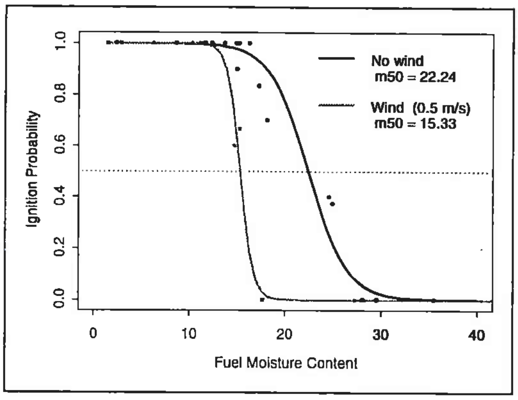

Figure 2. Ignition success in the absence and presence (0.5 ms^{-1}) of wind.

5. IGNITION THRESHOLDS OF DIFFERENT LITTER TYPES

Litter from ten different species were used for the experiments. These species are listed in Figure 3 and Table 1. The species chosen cover a wide range of particle sizes, shapes and morphologies, and are representative of common plants from eastern Australia, with emphasis placed on heathland species. Measurements of particle characteristics from 100 random samples from each litter type were made. These included particle weights, lengths, thicknesses, diameters, surface area, volume, density and surface area to volume ratio. These, along with the fuel weight of each bed prepared were used to calculate bed characteristics, such as bulk density and packing ratio. Particle and bed characteristics were used as predictor variables in models. Ignition probability data was modelled individually for each species and is illustrated in Figure 3.

There are vast differences in the ignition thresholds for the different litter types, as can be seen in Figure 3. Some species will ignite in conditions when others will not. Two of the species studied, *Banksia ericafolia* or *Leptospermum laevigatum*, failed to ignite even at very low fuel moisture contents. This was a surprising result, as these two species are known to exhibit intense fire behaviour in their aerial structures during bushfires. The litter from these species has the smallest particles

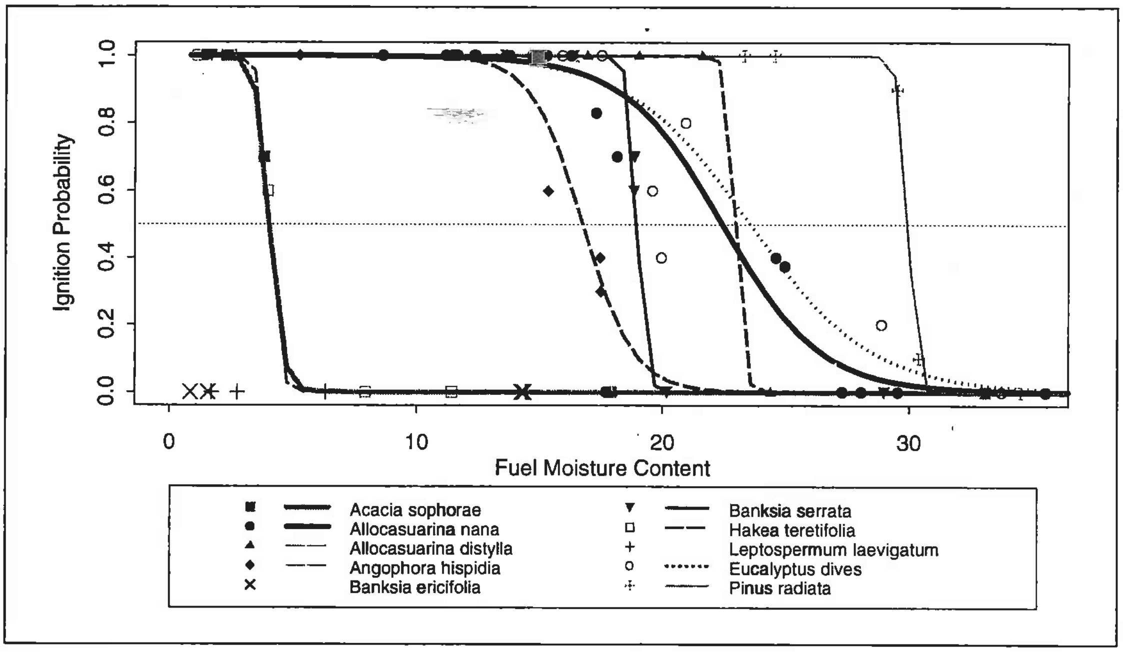

Figure 3. Ignition probability for the different litter types.

and the most dense fuel beds of the species studied. The slopes of the curves in Figure 3 are quite variable. The slopes of the models were found to be best explained by the coefficient of variation of the litter bed packing ratio. Generally species with large, fragile fuel particles had high proportions of broken fragments within their beds, and therefore more variable packing ratios. The models for these species had low gradient curves.

The data from the different litter types were combined and used to model the m_{50} of each species. The m_{50} correlated best with litter bed density (r=-0.75, p<0.01). Litter bed density (ρ_b) is related to the aeration of the fuel and is measured in kilograms per cubic metre. The relationship appears to be linear, apart from one outlying point, *Acacia sophorae*. *Acacia sophorae*, has a much lower m_{50} than would be predicted by the bulk density. Litter from this species was observed to burn at a much slower rate than litter from the other species. A linear model was fit to the data, excluding *Acacia sophorae*, and is given in Equation 1, and illustrated in Figure 4. Although linear equation fits the data well the form of the model is not ideal as it predicts fires to ignite when the density is zero. For this reason an alternative model, Equation 2, has been suggested. This model is more suitable than the linear model as it accounts for low-density litter beds, however it is only valid for the range of the data

$$m_{50} = -0.20\rho_b + 28.21 \qquad (1)$$

$$\ln(m_{50}) = -8.62 + 5.09\ln\rho_b - 0.18\rho_b \qquad (2)$$

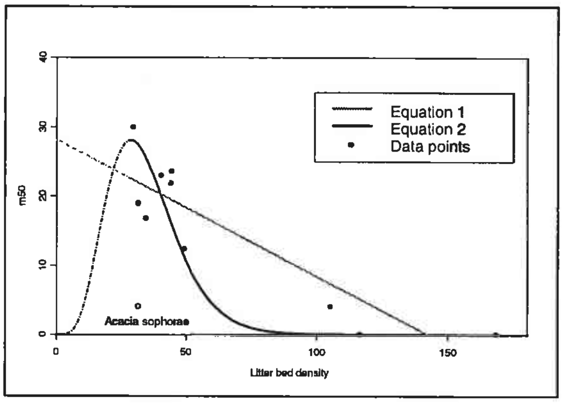

Figure 4. Fitted model of m_{50} using litter bed density.

Litter bed density does not explain all of the reasons for differences in the m_{50}'s. Other species effects are likely to come from non-physical parameters, notably litter flammability due to chemicals within the fuel. Little work has been done on fuel chemistry and its effects on flammability. Investigation of litter particle flammability is beyond the scope of this project.

The m_{50}'s given in Table 1 cover a wide range. The high m_{50}'s of species with low litter densities, typical of forest species, compare well with ignition thresholds given in the literature. Burrows [1999] found that head fires would not spread in laboratory experiments in *Eucalyptus marginata* litter fuels when the fuel moisture content was above 21%. Luke and McArthur [1978], state that moisture contents of 20-25% will prevent ignition. These seem comparable to the species with dense litter beds in this paper. There are no published figures for species with small particle litter.

Table 1. The m_{50} and bed density for the litter types studied.

Litter source species	m_{50} (% FMC)	ρ_b (kgm^{-3})
Acacia sophorae	4.1	31.5
Allocasuarina distylla	23.0	40.2
Allocasuarina nana	22.4	44.0
Angophora hispidia	16.8	34.5
Banksia ericafolia	No ignition	168.3
Banksia serrata	19.0	31.6
Eucalyptus dives	23.6	44.4
Hakea teretifolia	4.1	105.4
Leptospermum lavigatum	No ignition	116.4
Pinus radiata	30.0	29.6

6. CONCLUSIONS

All of the factors investigated; ignition source, wind, and species, affect ignition thresholds of litter. Fuel moisture has proven to be a practical predictor variable and the m_{50} is an effective indication of ignition threshold. Ignition thresholds are sensitive to the pilot ignition technique, with the size of the ignition source being of particular importance. Wind decreases the moisture content at which fires ignite when the pilot ignition source is on top of the litter bed, but is expected to have a different effect when pilot ignition is from within the litter. The influence that different litter species have on ignition thresholds is not completely apparent, but is best modelled using litter bed density.

This paper has not examined all of the parameters that affect litter ignition thresholds. Future work will investigate the effects of mixed species fuel beds, applying wind to other ignition sources, and raising the litter bed to increase aeration. Other factors such as wind speed, slope and fuel depth will not be studied due to time restrictions. The investigation of ignition of aerial fuels, such as shrubs, is of high priority. The results of these experiments will be combined with litter ignition results to develop ignition probability models to be used to create an ignition danger index. This could be aided by accompanying fuel moisture models, so that weather parameters could be used as inputs. The index would be useful in the planning of prescribed burning and could be added to fire models so they will only predict fire behaviour when fires can be ignited.

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