Drying of vegetation: how fast does the moisture go?

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Abstract

Live and dead vegetation both need to be dried out prior to combustion in a bushfire. This article presents a simple model that accounts for the heating that occurs inside a cylindrical vegetation sample which has a prescribed initial moisture content and is subjected to a heating regime characteristic of a passing bushfire. The model allows us to predict the death or survival of live vegetation samples of any given diameter. It can also be extended to include any thermal properties and any shape for the vegetation sample.

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1 Introduction

During the passage of a fire front, live and dead vegetation must be dried out prior to being available for combustion. Thermocouple traces of the temperature on the surface of vegetation samples [1] show that there is typically a very rapid rise of temperature as a fire approaches. This suggests that the drying of fine scale vegetation must occur over rather short time scales (seconds or, at most, minutes). Naturally, larger vegetation items, such as logs, dry out over a longer time scale, provided that heating from ongoing combustion continues, but for the present study we consider only smaller items that are either significantly dried out, or are even consumed during the immediate passage of the fire front. Specifically, we report on our efforts to develop a mathematically simple yet illustrative model that quantifies the moisture loss of a cylindrical sample of live vegetation during the passage of a fire front. In particular, we quantify the manner in which the presence of moisture slows down the rate of rise of the temperature inside the vegetation. The model for the heating of the vegetation is based upon the work reported in [1, 2] and the model formulated in [3], which accounts for the moisture content. A useful review of previous modelling work on heating vegetation can be found in [4] and while it anticipates the inclusion of moisture in the final model, it does not provide a framework for creating such a model. We believe that the resultant model for heating and drying is a new and useful approach.

2 Model A—no moisture

The simplest model is where the temperature rise $T(r,t)$ inside the vegetation is due only to heating by conduction and the thermal properties are those of dry vegetation, as considered in [1, 2]. We assume that we have a radially symmetric cylinder of vegetation with a prescribed temperature applied at the boundary:

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \nabla^2 T \,,$$

with the symmetry condition $\partial T/\partial r = 0$ in the centre at $r = 0$ and time dependent boundary condition $T = f(t)$ at $r = R$. We also assume that the vegetation cylinder is initially at ambient temperature T_a. In these equations, ρ is the density of the vegetation, c_p is the specific heat, and λ is the thermal conductivity. The values we use here to illustrate the use of the models are $\rho = 800\,\mathrm{kg\,m^{-3}}$, $c_p = 1370\,\mathrm{J\,kg^{-1}\,K^{-1}}$, $\lambda = 0.1\,\mathrm{W\,m^{-1}\,K^{-1}}$, ambient temperature $T_a = 296\,\mathrm{K}$ and the radius of the cylinder is $R = 0.01\,\mathrm{m}$. These are representative values chosen from [1, 2, 3].

The prescribed time dependent boundary temperature profile is also assumed to be radially symmetric and is prescribed in such a way that it simulates a passing fire front:

$$T(R,t) = f(t) = \begin{cases} T_a + \dfrac{A}{z} \exp\left(-\dfrac{(t-a)^2}{B^2 z^2}\right) , & t < a \,, \\[2ex] T_a + \dfrac{A}{z} \exp\left(-\gamma(t-a)\right) , & t > a \,. \end{cases}$$

Representative values we choose are $A = 250\,\mathrm{K\,m^{-1}}$, $a = 50\,\mathrm{s^{-1}}$, $B = \sqrt{200}$ $\mathrm{s^{1/2}\,m^{-1}}$, $\gamma = 1/200\,\mathrm{s^{-1}}$ and $z = 1\,\mathrm{m}$. Note that this gives a maximum temperature of $T_a + (A/z) = 546\,\mathrm{K}$ and the typical duration of the entire heating period is approximately 316 seconds (defined as the time for which the temperature is above 70°C).

3 Model B—including moisture

In a similar way to [3], we now introduce a model that includes moisture in an averaged way. When the vegetation is heated, any free or bound water is also heated and evaporates during the heating. By the time the boiling point of water, 373 K, is reached, all of the water will have been evaporated. This gradual drying out during the heating is included in the model by having different equations for temperatures above and below the boiling point of water. The model then becomes

$$\lambda\nabla^2 T = \begin{cases} \overline{\rho c}\frac{\partial T}{\partial t}\,, & T \leq 373\,, \\ \rho c_p\frac{\partial T}{\partial t}\,, & T > 373\,, \end{cases}$$

where the overline denotes an average density and specific heat capacity, defined according to

$$\overline{\rho c} = \rho\left(c_{p,\mathrm{wood}} + M c_{p,\mathrm{water}} + \frac{\mathcal{L}}{373 - T_a}\right).$$

Here M (typically $M = 0.077$ in later calculations) is the initial fractional moisture content, defined as the weight of the moisture as a proportion of the dry weight of the vegetation. This is a key parameter and it is related to the usually quoted percent moisture content by simply multiplying by 100. We now require the two specific heat capacities, $c_{p,\mathrm{wood}} = 1370\,\mathrm{J\,kg^{-1}\,K^{-1}}$ and $c_{p,\mathrm{water}} = 4186\,\mathrm{J\,kg^{-1}\,K^{-1}}$. Also, $\mathcal{L} = 2.254\times 10^6\,\mathrm{J\,kg^{-1}}$ is the latent heat of vaporisation of water at 373 K [3]. The boundary and initial conditions are assumed to be the same as in Model A.

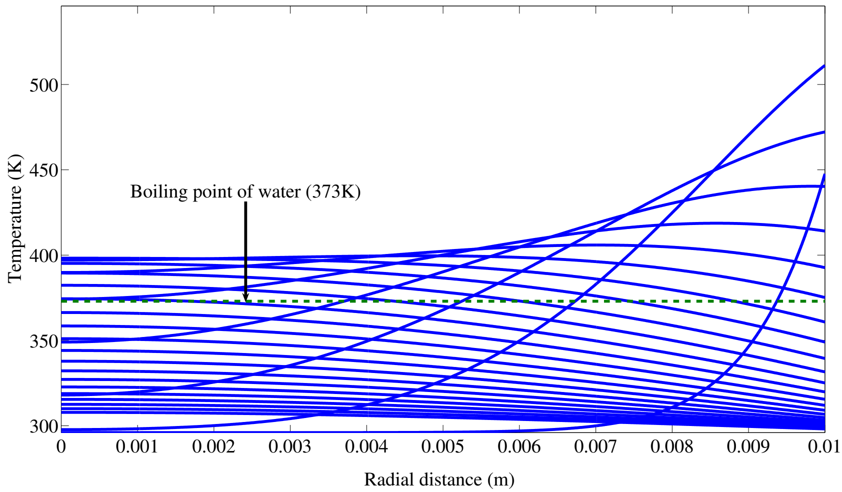
We emphasise that the use of the "average" parameter $\overline{\rho c}$ is a modelling technique that allows us to represent the actual moist vegetation with an equivalent vegetation which requires the same quantity of thermal energy to raise it to 373 K and to remove all of the moisture.

4 Comparison of the models

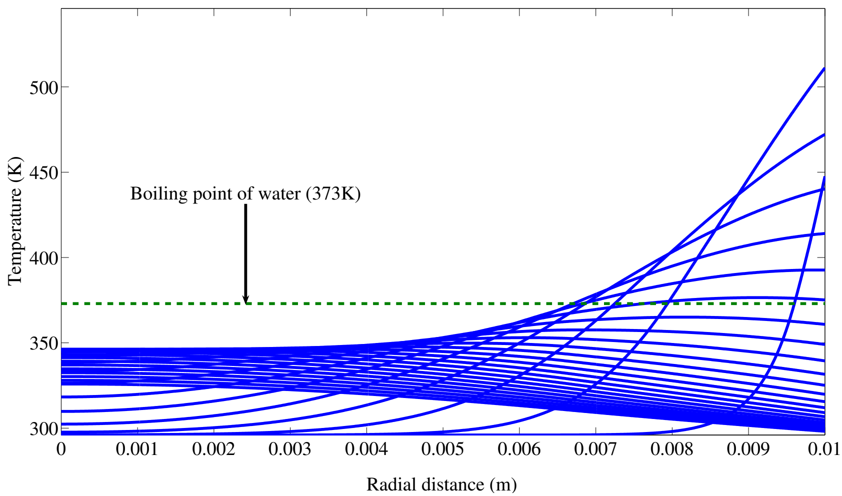
Models A and B are solved using a second order finite difference method, explicit in both time and space. Figure 1 shows the temperature profiles along a radial line in the vegetation cylinder for each of the two models. The first thing to note is that the inclusion of moisture results in the central temperature being significantly reduced to well below the boiling point of water, 373 K. The second thing to note is that Model A shows evidence of the rapid diffusion of heat towards the centre, whereas in Model B, the heat capacity is larger for the moist wood and, as expected, this hinders the diffusion until after the fire has passed.

The formulation of Model B, which has a step function in the heat capacity, means that the problem has effectively been changed into something akin to a Stefan problem, with a moving front whose temperature is 373 K. This front is an interface between vegetation which is still drying and vegetation which has completely dried. The motion of the front for models A and B is shown in Figure 2; the presence of moisture in model B results in the much slower motion of the front.

Figure 3 plots the temperature at the centre of the vegetation sample for both models A and B. Including moisture in the model results in a significant effect on the central temperature. With the representative parameter values, the central temperature in model B rises to its maximum of only 309 K after 250 seconds, which is long after the fire has passed. In comparison, the central temperature in model A rises to about 393 K.



(a)



(b)

Figure 1: The temperature profiles for (a) Model A (no moisture) and (b) Model B (moisture included)

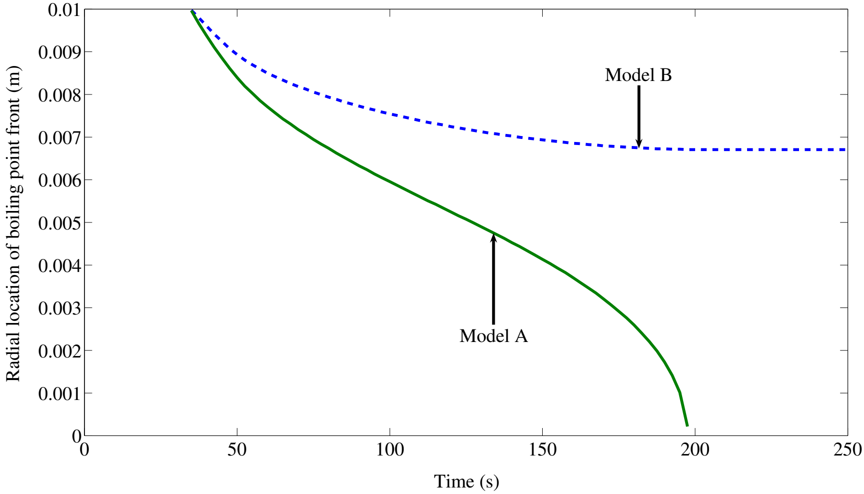


Figure 2: The location of the boiling point front (373 K) in Models A (no moisture) and B (moisture included).

One of the key topics [1] is the thermal death of a fruit or a seed. A typical criterion is that death will occur if the temperature at 20% of the radius from the centre of the seed reaches 70°C. We use a similar criteria appropriate to the inner radius of the bark of a tree. Specifically, we assume that the critical temperature is that found at 20% of the radius measured from the outside of the cylinder (or equivalently at 80% of the radius measured from the centre). Using the initial moisture content as an adjustable parameter, we find that a critical moisture content for the current example is 0.75 measured by dry weight (equivalent to 75% initial moisture content), as this is where the temperature at the inner radius (of the bark) just reaches 70°C before diffusing away. This is shown in Figure 4. This would suggest that the current heating regime will cause an adverse outcome to a vegetation sample of radius 0.01 m.

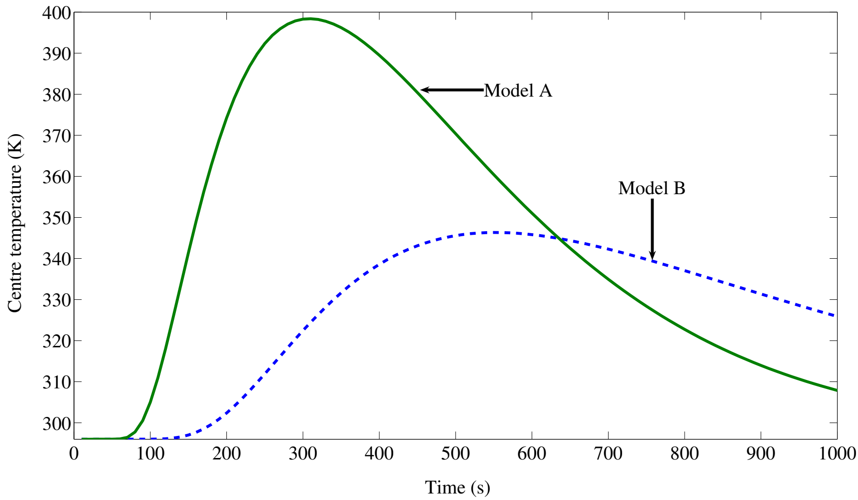


Figure 3: The central temperature for Models A (no moisture) and B (moisture included)

5 A further example

Using parameters taken from [1], we further examine the behaviour predicted by model B. The parameters are $\rho = 509\,\mathrm{kg\,m^{-3}}$, $D = \lambda/\rho c_p = 1.3 \times 10^{-7}\,\mathrm{m\,s^{-2}}$, $c_{p,\mathrm{wood}} = 1370\,\mathrm{J\,kg^{-1}\,K^{-1}}$, $c_{p,\mathrm{water}} = 4186\,\mathrm{J\,kg^{-1}\,K^{-1}}$. As for the boundary conditions for the outside of the tree, the fitted parameters, for a fire passing with thermocouples at a height of $z = 3.5\,\mathrm{m}$, are $A = 1172.1\,\mathrm{K\,m^{-1}}$, $B = 4.8342\,\mathrm{s^{1/2}\,m^{-1}}$ and $\gamma = 0.012932\,\mathrm{s^{-1}}$. We also chose $a = 50\,\mathrm{s}$, the time shift, to give enough time before the fire front arrives.

Going back to the previous point about thermal death when the temperature at 80% of the radius reaches 70°C, for a given radius of tree, we can work out what the critical initial moisture content has to be so the tree survives. Conversely, we could for a given moisture content specific to any vegetation sample, determine the critical radius so that it survives, as shown

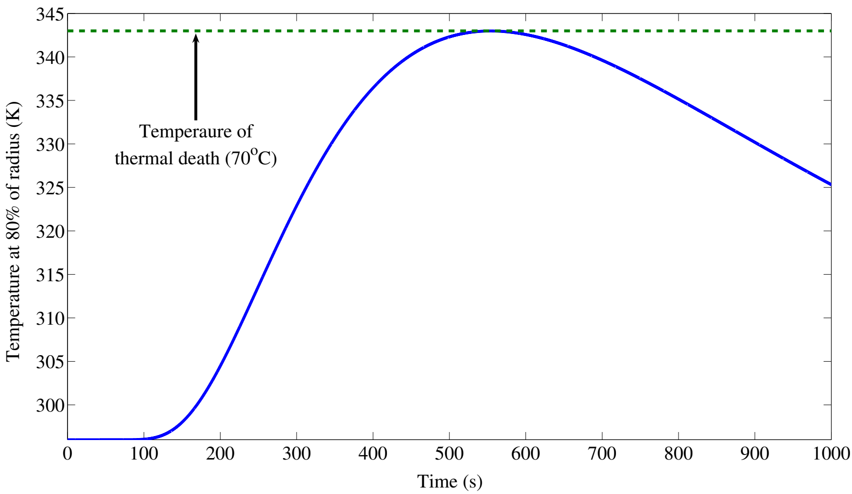


FIGURE 4: The temperature-time profile at 80% of the radius, for Model B calculated with a radius of 0.01 m and an initial fractional moisture content of 0.75 .

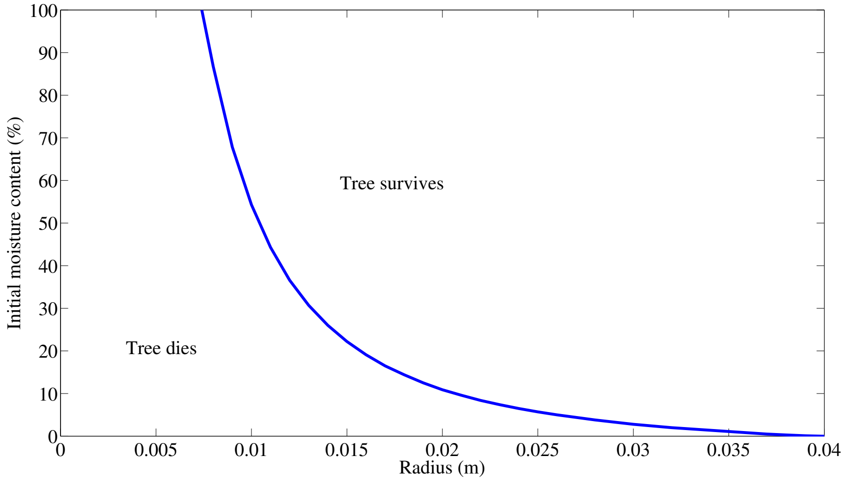


Figure 5: The critical initial moisture content for a given radius for a tree to survive/die through thermal death, using model B and the parameters in Section 5.

in Figure 5. For the parameters quoted at the start of this section, we find that a tree of radius of 0.04 m or above will survive the fire, even if there is no initial moisture. We also find that for a tree of radius of 0.007 m or less, even if the tree has a moisture content of 100%, it is still going to die.

6 Conclusion

We have presented a model for the heating of vegetation samples and included the thermodynamics of the consequent moisture loss in a simple, yet sensible manner. This illustrates the effect of a particular heating scenario on a cylindrical sample, showing the effect of initial moisture content and finding the critical initial moisture content for survival. Any desired heating scenario for any size sample could be examined in the same way and a suitable conclusion determined. Indeed, the method could also be extended to any shape of vegetation sample and also to multi-layer cylindrical samples, so that a full range of fruits, seeds, branches and tree trunks, can be studied using the model developed in this article.

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