Heat budget and fire behaviour associated with the opening of serotinous cones in two Pinus species

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Abstract. We have constructed a heat budget for the transient heating of cones showing that there is a logarithmic relationship between the time (sec) to serotinous cone opening, releasing viable seeds, or cone ignition and temperature (°K) in the convective column above a fire. The rate of opening at a given temperature is controlled by a thermal time constant which is the ratio of the thermal resistance of a cone to convection, to the heating capacity of a cone by conduction. The observed times to cone opening and ignition fit the logarithmic relationship as predicted by the heat budget model. In order to understand the fire behaviour that results in cone opening and ignition, we changed the variables of temperature and time to the fire behaviour variables of fire intensity (kW/m) and fire rate of spread (m/min). Cones borne high in the canopy open in fires with low rates of spread and high fuel consumption, where intensity = rate of spread × fuel consumption × heat of ignition, but not when the rate of spread is high and fuel consumption low.

Keywords: Fire ecology; Heat budget model; Pinus banksiana; Pinus contorta var. latifolia.

Introduction

Unlike the cones from most coniferous trees, cones of Pinus banksiana Lamb. and Pinus contorta var. latifolia Engelm. do not open spontaneously after maturation. These serotinous cones remain closed until they are heated, usually by a forest fire. Serotinous cones are an excellent example of an adaptation to recurrent disturbance by fire (Perry & Lotan 1979; Muir & Lotan 1984). However, little is known about the mechanisms by which fires open cones and the relationship of these mechanisms to the types of fires that result in cone opening.

Serotinous cones remain closed because of resins which seal the cone scales together. If sufficient heat is applied to the cone for some period of time, the resin bonds weaken and break, the cone scales reflex away from the cone axis, and seeds are released. Consequently, the opening of serotinous cones is at least a two-part process: (1) the resin bonds weaken and break, and (2) the cone scales reflex away from the cone axis.

The reflex mechanism of the cone scales is well understood (Harlow, Côté & Day 1964). Cone scales consist of two types of cells: dorsal cells are wood fibers oriented along the cone scale axis and ventral cells are short rectangular sclerenchyma cells which have microfibrils oriented at 90° to the cone scale axis. When the scales dry, the dorsal cells shrink 0.5% or less while the ventral cells shrink 10 - 36% in length. This differential shrinkage causes the cone scale to reflex. The greater the difference in moisture content of the scale at the start and end of drying, the greater the degree of flexing.

Little has been done to define the mechanisms of heat transfer which cause the resin bonds to weaken and break. Past studies have used temperature as a facile explanation for these heat transfer mechanisms (Crossley 1956; Perry & Lotan 1977; Hellum & Pelchat 1979; Hellum & Barker 1980, 1981). Clearly, the cone’s temperature does not rise instantaneously to the same temperature as the heated ambient air. Resistance to heating occurs across the cone’s boundary layer and through the cone itself. Further, the heating is not steady state, but is transient, with a temperature gradient between the surface and interior. A good example of the limitations of temperature is a study by Cameron (1953). He extracted the resin from six cones each of Pinus banksiana and Pinus contorta var. latifolia and determined the mean melting temperatures to be 50.0 °C and 45.5 °C respectively. This approach ignores the resistance of cones to heating and does not define the heat transfer process.

The best study on cone opening and cone ignition is by Beaufait (1960). He recognized that the amount of time a cone is heated is important and constructed an empirical graph showing an exponential relationship between the temperature of heated ambient air and the time of exposure to these temperatures that results in cone opening and cone ignition. Unfortunately, he did not propose a heat transfer mechanism to explain this pattern.

Our purpose here is to: (1) construct a simple heat budget model that describes the mechanisms of transient cone heating, and (2) define the types of fire that
Johnson, E. A. & Gutsell, S. L.

result in cone opening and viable seed release. First, we will describe the heat budget in terms of the heating processes. Then we will explain how the thermal properties for the heat budget were determined. Next, we will compare the time and temperature of cone opening and ignition for cones observed, to that calculated by the heat budget model. Finally, we will relate cone opening and ignition to fire behavior characteristics, fire intensity (kW.m\(^{-1}\)) and rate of spread (m.min\(^{-1}\)) in order to address which types of fire result in cone opening and viable seed release.

**Cone heat budget model**

The heating of cones occurs by the processes of conduction (Fourier’s Law) and convection (Newton’s Law of Cooling). The heat budget in terms of conduction and convection respectively is:

\[
\rho cv \frac{dT}{d\tau} = -hA(T_o - T_f)
\]

where \(\rho\) is the density (kg·m\(^{-3}\)), \(c\) is the specific heat (kJ·kg\(^{-1}\)·°K\(^{-1}\)), \(v\) is volume (m\(^3\)), \(\tau\) is time (sec), \(h\) is the film heat transfer coefficient (kW·m\(^{-2}\)·°K\(^{-1}\)), \(A\) is surface area (m\(^2\)), \(T_o\) is ambient temperature (°K), and \(T_f\) is temperature in the convective column above a flame (°K). The temperatures can be replaced with the dimensionless temperature \(\theta\) defined as:

\[
\theta = \frac{T_i - T_f}{T_o - T_f}
\]

where \(T_i\) is the melting point of the cone scale resin (318 °K) or the temperature at which the resins and volatiles issuing from the cone ignite: 333 °K for *Pinus contorta* and 373 °K for *Pinus banksiana*. The resin melting temperature for cones was taken from measurements by Cameron (1953) and the ignition temperature was taken from our observations. The dimensionless temperature \(\theta\) is the effective heating rate. In this case, low values of \(\theta\) mean that the flame convective temperature is low and high values of \(\theta\) mean that the flame convective temperature is high.

Substituting \(\theta\) for temperature and rearranging equation (1) results in:

\[
\frac{d\theta}{d\tau} = -\frac{hA}{\rho cv} (\theta)
\]

Solving equation (2) for the initial conditions of \(\tau = 0\) and \(\theta = 1\) gives:

\[
\theta = \exp \left( -\frac{hA}{\rho cv} \right) \tau
\]

The coefficient \((hA/\rho cv)\), called the thermal time constant (sec\(^{-1}\)), contains the thermal properties of a cone that determine the rate at which it will be heated. The numerator \((hA)\) is the thermal resistance to convection and the denominator \((\rho cv)\) is the heating capacity by conduction. Large values of this thermal time constant indicate that a cone will undergo a rapid temperature change while small values indicate a slower temperature change.

The product of the coefficient \((hA/\rho cv)\) and time \(\tau\) will be called dimensionless time. This dimensionless time allows a comparison between cones despite any differences in their thermal properties.

The model, equation 3, is based on the assumption that the resistance through the interior of the cone is low relative to the resistance through the film boundary layer over the cone surface. The Biot number, \(N_{Bi}\), is a dimensionless parameter which expresses this relative resistance. It is given by:

\[
N_{Bi} = \frac{hDk^{-1}}{}
\]

where \(D\) is cone diameter (m) and \(k\) is thermal conductivity (kW·m\(^{-1}\)·°K\(^{-1}\)). Small values of \(N_{Bi}\) indicate that the internal resistance is negligible (i.e. there is a small internal temperature gradient) and thus the heat flux into the cone is regulated by the resistance through the boundary layer.

The relative thickness of the boundary layer depends solely on the Reynolds number, Re, which is given by:

\[
Re = \frac{UD}{\nu}
\]

where \(U\) is air velocity (constant = 0.5 m/sec) and \(\nu\) is kinematic viscosity (of air = 1.5 \times 10^{-5} m^2·sec\(^{-1}\)). Lower values of Re indicate a thicker boundary layer.

**Methods**

Cones of *Pinus banksiana* were obtained from Prince Albert National Park, Saskatchewan. Cones of *Pinus contorta* var. *latifolia* were obtained in the Kananaskis Valley 150 km west of Calgary, Alberta. Both areas have only serotinous cone populations.

Time for cone opening and cone ignition were measured in an open muffle oven set at temperatures ranging from 70 °C to 845 °C. The time for cone opening was determined by listening for a cracking noise indicating
Heat budget and fire behaviour associated with opening of serotinous cones

The cones were placed 1.5 cm from a pilot flame inside the oven to determine time of ignition. The temperature inside the oven was measured by an OMEGA model OS-2000A pyrometer.

Surface area (m²) of the cones was measured using Poropak™ which forms a monolayer on the cone surface. Knowing the Poropak surface area-weight relationship we determined the cone surface areas by measuring the weight of the cones before and after the addition of Poropak. Volume (m³) of the cones was determined using the water displacement method. Density (kg·m⁻³) of cones was calculated by dividing dry weight by volume. Moisture content was taken as the difference between wet weight and dry weight and dividing by dry weight. Specific heat of wet wood is given by the equation:

\[ C_{\text{wet}} = C_{\text{dry}} + \frac{4.19}{(1 + M)} + \left(0.02355T_f - 1.32M - 6.191\right)M \] (kJ·kg⁻¹·K⁻¹)

where \( M \) is fractional moisture content on a dry weight basis and \( T_f \) is convective flame temperature (°K) (Ragland, Aerts & Baker 1991). The specific heat of dry wood is given by the equation:

\[ C_{\text{dry}} = 0.001758T_f - 0.55144 \] (kJ·kg⁻¹·°K⁻¹)

derived from Differential Scanning Calorimetry data by Susott (1982). The film heat transfer coefficient \( h \) for cones is given by the equation:

\[ h = \frac{Q}{\pi D^2(T_o - T_f)} \] (kW·m⁻²·°K⁻¹)

where the radiant heat flux \( Q \) follows the Stephan-Boltzmann Law and \( D \) is cone diameter (m). Specific gravity, \( s \) (mass density), was determined using the methods outlined in the Annual Book of ASTM Standards (Anon. 1978). Thermal conductivity, \( k \), is given by the equation (Ragland, Aerts & Baker 1991):

\[ k = s \left(0.1941 + 0.4064M\right) + 0.01864 \] (W·m⁻¹·°K⁻¹)

In order to show the cone opening and cone ignition in terms of the actual fire behaviour we converted the model’s temperature and time variables for cone opening and cone ignition to fire intensity (kW·m⁻¹) and fire rate of spread, respectively.

To convert temperature \( T_f \) to fire intensity, we used the equation given by Thomas (1963):

\[ \Delta T = bP^{2/3}z^{-1} \]

or

\[ P^{2/3} = \Delta Tzb^{-1} \] (4)

where the temperature rise, \( \Delta T \), is the difference between the ambient temperature \( T_o = 20°C \) and the temperature in the convective column at which cones open, \( T_c \), \( z \) is height above the ground (m) and \( b \) is an empirical constant \( 2.39°C·m^2·kW^{-1} \) given by Van Wagner (1975). Using this equation we can determine the fire intensity at a given height above the ground. The heights chosen are 10 and 20 m since mature Pinus banksiana and Pinus contorta in our study area can carry their cones over this range. For convenience we are assuming that the trees are 10 and 20 m tall and that most of the cones are borne at the top of the tree.

To convert time \( t \) to rate of fire spread, \( R \), we used the following equation:

\[ R = \frac{dt}{d} \] (5)

where \( d \) is the horizontal depth of the flame (m) and \( t \) is the residence time of the flame (min). From this equation we can determine the rate of spread using the time \( \tau \) to cone opening or cone ignition as a measure of \( t \). The horizontal depth of the flame chosen is 2 m.

In order to determine the height of crown scorch, \( z_s \), for the fire intensity at which cones are opening, we used the equation given by Van Wagner (1973):

\[ z_s = 0.09196I^{2/3} \] (6)

In order to determine the total fuel consumption (kg·m⁻³) for the fire intensity and fire rate of spread at which cones open, we used the equation given by Byram (1959):

\[ I = HWR \] (7)

where \( H \) is heat of ignition (12 700 kJ·kg⁻¹), and \( W \) is total fuel consumption (kg·m⁻²).

Results and Discussion

Fig. 1 shows the relationship between the empirically determined temperature \( T_f \) of cone opening and the dimensionless time \( \tau' = \frac{\tau \cdot hA}{pce} \) for both species Pinus banksiana and Pinus contorta. The solid line represents the logarithmic relationship proposed by the heat budget model, equation 3. Variation around the line for cone opening is due to the difficulty encountered in listening for the cracking noise indicating resin bond breakage. At low temperatures the larger observed values for time to cone opening may have been a result of our inability to hear the resin bonds breaking due to the slowness of
Fig. 1. The empirically determined dimensionless time to cone opening over a temperature range (shown both as real temperature and dimensionless temperature) with the exponential relationship (---) proposed by the heat budget model (equation 3). The solid symbol (●) denotes *Pinus banksiana* and the open symbol (○) denotes *Pinus contorta*.

The melting process. At the highest temperatures, the larger observed times to opening may have been due to our inability to time the breaking bonds fast enough since time to opening was so short (2-3 sec).

Figs. 2a and 2b show the relationship between the empirically determined temperature ($T_i$) of cone ignition and the dimensionless time $\left( \tau \cdot \frac{h A}{\rho c v} \right)$ for *Pinus contorta* and *Pinus banksiana* respectively. Variation around the line for cone ignition is due to the uneven volatilization of the resins around the cone and the small size of our pilot flame. There are at least two possible explanations for the differences in cone ignition between *Pinus contorta* ($T_i = 100$ °C) and *Pinus banksiana* ($T_i = 60$ °C); (1) the volatiles available for ignition are different between the two cone types; or (2) the thermal coefficient ($h A / \rho c v$), is not as appropriate for combustion as it was for cone opening. For convenience, the remainder of the Discussion will use cone ignition in *Pinus contorta*, Fig. 2b.

Table 1 shows the variability in the cone-thermal properties of *Pinus banksiana* and *P. contorta*. The calculated average Biot number for the cones is 0.01295 with a standard deviation of 0.00999. The calculated average Reynold's number for the cones in the experimental set-up, assuming wind speed = 0.5 m·sec⁻¹ and kinematic viscosity of air = $1.5 \times 10^{-5}$ m²·sec⁻¹, is of the order 1000.

We have adopted a very simple heat budget model which relates the time to cone opening or cone ignition to both the temperatures in the convective column above a fire and the thermal properties of cones. Although simple, the model does trace the patterns of our data. Also, it clearly fits the patterns of cone opening and cone ignition given by Fig. 1 in Beaufait (1960). This model is superior to the previous use of temperature alone as an indicator for cone opening because it gives...
the complete suite of variables involved in cone opening. It postulates how the thermal properties of cones, the temperature and the time affect cone opening. However, we have made a number of simplifying assumptions. One assumption is that the moisture loss during heating is slow enough so that the initial value of thermal conductivity is not affected by moisture loss. Also, notice that we have not taken into account that there are often thermally generated winds in a wildfire such that the Reynolds’s number may be in fact higher in wildfires than the ones we have calculated in the laboratory. Both of these assumptions can be tested in the field.

Knowing the heat budget for cone opening and ignition however does not in itself help us understand the fire behaviour (fire intensity and fire rate of spread) over which cones will open. By converting the temperature variable to fire intensity $I$ (kW-m$^{-1}$), and the time variable to the fire rate of spread $R$ (m-min$^{-1}$) we can then show the cone opening and cone ignition in terms of the actual fire behaviour.

Figs. 3a and 3b represent Figs. 1 and 2b in terms of the fire behaviour variables of intensity and rate of spread, recalculated using equations 4 and 5. The figures give the combinations of intensity and rate of spread that define the conditions under which cone opening occurs and viable seeds are released. For example, using the cones at the 10 m height (Fig. 3a), a fire with intensity less than 900 kW-m$^{-1}$ will never produce enough heat to open cones, no matter how low the rate of spread (i.e. how high the residence time). When the intensity is > 6000 kW-m$^{-1}$, at these same low rates of spread, the cones will ignite, killing the seeds. Consequently, in trees that are 10 m tall, when fire intensities are between 900 and 6000 kW-m$^{-1}$ and have low rates of spread, we expect cones to open but not ignite. As the values of intensity and rate of spread increase, cone opening increases rapidly.

*Pinus banksiana* and *Pinus contorta* regenerate best when there is full sunlight on the ground and exposed mineral soil. Using equation 6, we calculated the height of crown scorch for each intensity at which cones are

### Table 1. The range in thermal properties found in cones of *Pinus banksiana* and *P. contorta.*

<table>
<thead>
<tr>
<th>Property</th>
<th><em>Pinus banksiana</em></th>
<th><em>P. contorta</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface area, $A$ (m$^2$)</td>
<td>0.00229 - 0.00788</td>
<td>0.00335 - 0.01260</td>
</tr>
<tr>
<td>Volume, $v$ (m$^3$)</td>
<td>0.004 - 0.021</td>
<td>0.006 - 0.026</td>
</tr>
<tr>
<td>Density, $\rho$ (kgm$^{-3}$)</td>
<td>0.595 - 1.064</td>
<td>0.761 - 0.899</td>
</tr>
<tr>
<td>Specific heat, $c_{\text{wet}}$ (kJkg$^{-1}$·K$^{-1}$)</td>
<td>4.078 - 7.560</td>
<td>4.043 - 7.463</td>
</tr>
<tr>
<td>Film heat transfer coefficient, $h$ (kWm$^{-2}$·K$^{-1}$)</td>
<td>0.013 - 0.241</td>
<td>0.031 - 0.346</td>
</tr>
<tr>
<td>Dry weight (kg)</td>
<td>0.004 - 0.017</td>
<td>0.005 - 0.021</td>
</tr>
<tr>
<td>Moisture content, $M$ (% dry weight)</td>
<td>0.037 - 0.330</td>
<td>0.022 - 0.177</td>
</tr>
<tr>
<td>Specific gravity, $s$</td>
<td>0.794 - 1.114</td>
<td>0.888 - 0.922</td>
</tr>
<tr>
<td>Thermal conductivity, $k$ (kWm$^{-1}$·K$^{-1}$)</td>
<td>0.00020 - 0.00030</td>
<td>0.00020 - 0.00023</td>
</tr>
</tbody>
</table>
opening. At approximately 900 kW·m⁻¹ a 10-m tree will be completely scorched (killed). This is also the lowest intensity rate of spread combination for a 10-m tree in which cones will open. In other words, over the entire range of intensity and rate of spread in which cones will open in 10-m trees, the canopy will be killed. Similarly, at ca. 3000 kW·m⁻¹ a 20-m tree will be completely scorched (Fig. 3b). This is the lowest intensity rate of spread combination in which cones will open in 20-m trees. Over the 10-20 m range of heights, if the cones are opening (see Fig. 3), then the canopy will also be killed.

Using equation 7, we calculated the total fuel consumption for the fire intensity and the fire rate of spread at which cones open. If \( I = 900 \text{ kW·m}^{-1} \) and \( R = 0.12 \text{ m·min}^{-1} \) the calculated surface fuel consumption is 39 kg·m⁻². Thus this lowest intensity and rate of spread in which cones will open (see Fig. 3) result in fires with very high fuel consumption.

In trees 10 - 20 m in height, their cones open and release viable seeds in fires with low rates of spread and high fuel consumption but not when the rate of spread is high and fuel consumption low. Consequently, fires with high rates of spread which have high fuel consumption result in a canopy that is killed and a forest floor on which a large amount of the mineral soil is exposed.

As tree (cone) height decreases, however, there is an increase in the range of fire intensity and rate of spread at which cones will open and release viable seeds. The types of fire opening cones will now include those with lower intensities and higher rates of spread. Thus, lowering the cone height increases the kinds of fire behaviour which leads to cone opening while raising the cone height limits the kinds of fire to slow moving, high fuel consumption burns. What we have shown is that there is a coupling between the birth (release) of seeds and the fire behaviour which is controlled by the height of cones above the ground.

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