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How Fires Cause Fire Scars on Trees: Coupling a Disturbance Process to its Ecological Effect

by

Sheri Lea Gutsell

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "How Fires Cause Fire Scars on Trees: Coupling a Disturbance Process to its Ecological Effect" submitted by Sheri Lea Gutsell in partial fulfilment of the requirements for the degree of Master of Science

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ABSTRACT

Four key observations associated with the formation of fire scars on trees are explained using fluid dynamics and heat transfer processes. (1) When a fire passes by a tree, its length increases on the tree's leeward side because two leeward vortices form. The flame height increases once in the vortices because the turbulent mixing of fuel and air is suppressed. The flow of gaseous fuel in the vortices becomes greater than the rate of mixing with the air and hence there is an increased length along which combustion can occur. (2) Fire scars are found only on the leeward side of trees because the vortices increase the residence time of the standing leeward flame. (3) Small trees rarely have fire scars because their cambium is usually completely killed by the passing fire and/or their foliage is killed by crown scorch. (4) Fire scars are usually triangular because the temperature isotherms in the standing leeward flame are triangular.

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Greek Symbols		Units
α	thermal diffusivity	m^2/s
θ	dimensionless temperature	dimensionless
τ	residence time	s
τ_f	residence time of free moving flame	s
τ_l	residence time of standing leeward flame	s
υ	kinematic viscosity	m^2/s

English Symbols		
d	tree diameter	m
d_f	diameter of the flame	m
erf	error function	dimensionless
h	surface coefficient of heat transfer	W/m^2 °C
h_s	height of crown scorch	m
h_t	height above fire	m
I	fire intensity	kW/m
k	thermal conductivity	W/m °C
R	fire rate of spread	m^2/s
Re	Reynolds number around cylinder	dimensionless
Re_f	Reynolds number of flame	dimensionless
T_c	temperature of cambial death	°C

T_f	temperature in the flame	°C
T_o	temperature of the cambium before heating	°C
U	upstream wind velocity	m/s
U_f	vertical velocity of fuel in burner	m/s
w	depth of flame	m
x	bark thickness	m

INTRODUCTION

The process-response approach to solving ecological problems couples a disturbance process to the biophysics of an organism and this in turn to an ecological effect (Johnson 1984). The advantage of this approach is that all parts of the causal pathway must be defined. One commonly observed ecological effect lacking this coupling is fire scars on trees (Figure 1). A fire scar is a result of partial cambial death at the base of a tree. There are at least four phenomena associated with the formation of fire scars on trees: 1) when a fire passes by a tree (either a head or backing fire) it increases in height on the leeward side of the tree (relative to the wind direction); 2) fire scars are found only on the leeward side of trees; 3) small trees rarely have fire scars; and 4) fire scars are usually triangular shaped, becoming narrower with height.

Past studies investigating fire scar formation have explained some aspects of the above four phenomena; however there have been few causal mechanisms given. Gill (1974) and Gollahalli and Brzustowski (1971) found that when a fire passed by a tree, it increased in height on the leeward side of the tree. Gill (1974) recognized that the presence of this standing leeward flame was related to tree diameter, wind speed and position of the tree relative to the flame; however, he gave no explanation of the mechanisms that result in this increased flame height. Fahnestock and Hare (1964), Hare (1965a), and Tunstall *et al.* (1976) found, in wind blown fires, that the

Figure 1. A typical fire scar on *Pinus banksiana*. Notice the triangular shape, decreasing in width with height. Photo by E.A. Johnson.

temperature is significantly higher on the leeward side of a tree, compared to all other sides. Fahnestock and Hare (1964) recognized that the increased heating on the leeward side of a tree is due to the chimney effect of a convection column but there is no explanation given for how this chimney effect occurs. A number of other studies (Hare 1961, Martin 1963, Fahnestock and Hare 1964, Gill and Ashton 1968, Hare 1965b, Spalt and Reifsnyder 1962, Tunstall *et al.* 1976, Vines 1968) have found that bark is important in preventing cambial damage by fire. Specifically, Hare (1961), Martin (1963), Spalt and Reifsnyder (1962), Hare (1965b), Vines (1968) and Gill and Ashton (1968) showed that the thermal properties and thickness of bark are important in preventing cambial death. Spalt and Reifsnyder (1962) and Vines (1968) give a semi-infinite slab model for the conduction of heat through bark. The model shows that the time it takes to kill the cambium through the bark is directly related to the square of bark thickness. Hare (1965b) and Vines (1968) confirm empirically that the time required to raise the cambium to a lethal level of 60°C is directly proportional to the square of bark thickness. These studies will be addressed later within the heat transfer mechanisms.

The purpose of this thesis is to present the mechanisms which lead to cambial death and the formation of fire scars on trees. First, I will present each of the mechanisms of fire scar formation, then I will give the methods used to test the proposed mechanisms and finally I will give evidence to show that the mechanisms proposed seem to explain all of the above four phenomena.

Mechanisms of Fire Scar Formation

The mechanisms which cause cambial death at the base of a tree will be discussed as follows: 1) air flow around a tree and the formation of leeward vortices; 2) the position and flow pattern of leeward vortices; 3) the interaction of leeward vortices with a free moving turbulent diffusion flame, causing differential heating around the base of a tree; and 4) heat transfer through the bark, from the standing leeward flame, which kills the cambium.

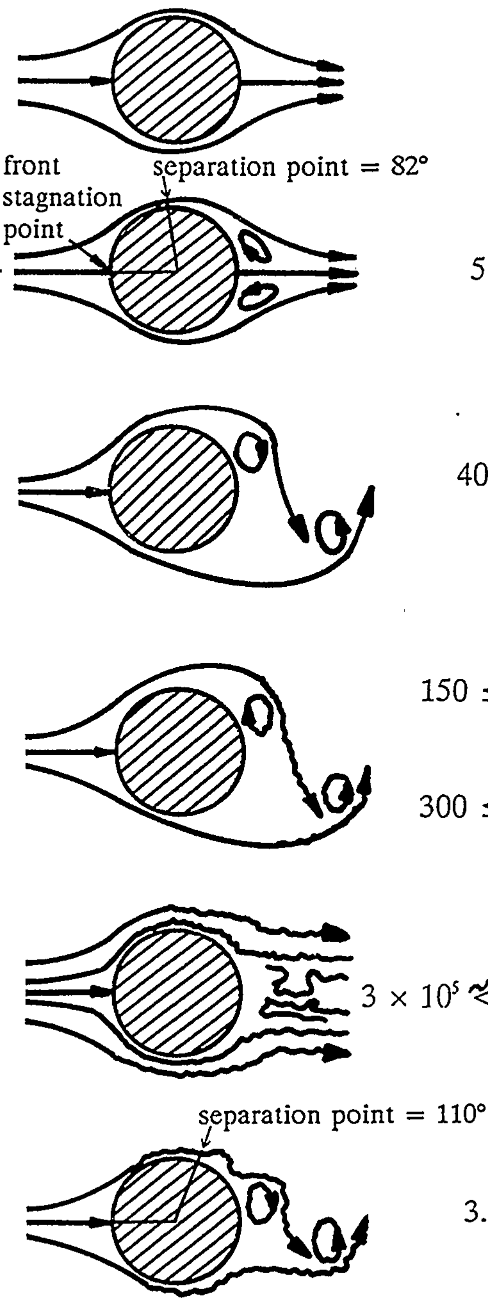
Air Flow and the Formation of Leeward Vortices

As air flows around the bole of a tree, a reverse flow occurs on the leeward side of the tree which produces a pair of vortices. This phenomenon is a well described process of separated flow behind a cylinder (von Kármán 1921, Goldstein 1938). The formation of these vortices depends on the upstream wind velocity, U (m/s), diameter of the tree bole, d (m), and kinematic viscosity of the air, υ (m^2/s). These variables can be combined to form the Reynolds number (Re),

$$Re = \frac{dU}{\nu} \tag{1}$$

The Reynolds number is a dimensionless number which characterizes air flow patterns and the formation of leeward vortices (Figure 2). Kinematic viscosity increases with an increase in air temperature as a fire approaches a tree; however the effect on the flow pattern is small relative to the effects caused by wind velocity and tree diameter. For example, at 0°C the kinematic viscosity is 1.32×10^{-5} m^2/s,

Figure 2. Flow patterns of air around a tree bole as characterized by the Reynolds number.



a)	$Re < 5$	laminar unseparated flow
b)	$5 \leq Re < 40$	pair of attached vortices
c)	$40 \leq Re < 150$	laminar vortex street
d)	$150 \leq Re < 300$	transition from laminar to turbulent vortex street
	$300 \leq Re \lesssim 3 \times 10^5$	fully turbulent vortex street
e)	$3 \times 10^5 \lesssim Re < 3.5 \times 10^6$	transition from laminar to turbulent boundary layer
f)	$3.5 \times 10^6 \leq Re$	re-establishment of turbulent vortex street

while at 40°C the kinematic viscosity is 1.69×10^{-5}. If tree diameter = 0.2 m and wind speed = 0.6 m/s, then the Reynolds number at 0°C = 9.1×10^{3}, while the Reynolds number at 40° = 7.1×10^{3}. Notice the order of magnitude has not changed. Consequently, the flow pattern is governed primarily by wind velocity and tree diameter. When the Reynolds number is less than 5, the flow around a tree is laminar (Figure 2a). Between 5 and 40, a pair of adjacent vortices form on the leeward side of the tree (Figure 2b). Above 40, the vortices will alternately detach, producing a wake of vortices called a vortex street (Figure 2c). Notice that, with a constant wind speed, trees with a smaller diameter will have lower Reynolds numbers than larger trees.

The Position and Flow Pattern of Leeward Vortices

The vortices on the leeward side of a tree are located between the two points of flow separation. Separation occurs where the air flow in the boundary layer along the surface of the tree bole no longer follows the contours of the tree (see Figure 2b). The point of separation depends on the value of the Reynolds number in the boundary layer along the tree. If the Reynolds number is less than 3×10^{5}, then the flow will separate at 82° (Potter and Foss 1975) from the front stagnation point (Figure 2b). The boundary layer undergoes a transition from laminar to turbulent flow when the Reynolds number is between 3×10^{5} and 3.5×10^{6} (Figure 2e). The increased turbulence in the boundary layer is transported by momentum from the free moving air to the slowly moving air in the boundary layer. This moves the separation point to a greater distance downstream on the tree, to 110° (Figure 2f). The position of the separation points at the base of a tree corresponds to the outer edges of the killed area on a fire scar.

Each vortex on the leeward side of a tree consists of two zones of flow: an outer zone of flow which is irrotational and an inner zone of rotational (solid body) flow (Figure 3). In the irrotational zone, the flow is translated around the inner zone with little rotation, that is, with no change in the fluid's orientation. For this orientation to be maintained, the air particles in the outermost region must have a lower tangential velocity than the air particles nearer the centre (Figure 4). The tangential velocity and radius in the inner zone of rotational flow have the opposite relationship. The air nearer the centre has a lower tangential velocity than air towards the outer edge of the zone and angular momentum is conserved (Figure 4). Consequently, particles in the rotational zone will change their orientation as they rotate (Figure 3). Conservation of angular momentum simply means that no matter where you are in the vortex core, there will be a constant value of angular momentum, since momentum is a function of particle mass, tangential velocity and radius of the vortex core. These patterns of flow play an important role in explaining the presence of the standing leeward flame as a free moving flame passes by a tree.

The Interaction of Leeward Vortices with a Turbulent Diffusion Flame

In forest fires, the free moving flame is a turbulent diffusion flame. It is turbulent

Figure 3. The patterns of flow in a vortex showing the zones of irrotational and rotational flow. If we follow the path of a particle, we can see how particle movement is different in each flow region. Notice that the orientation of a particle changes as it moves around the zone of rotational flow while its orientation does not change in the irrotational zone (*ie.* it is translated).

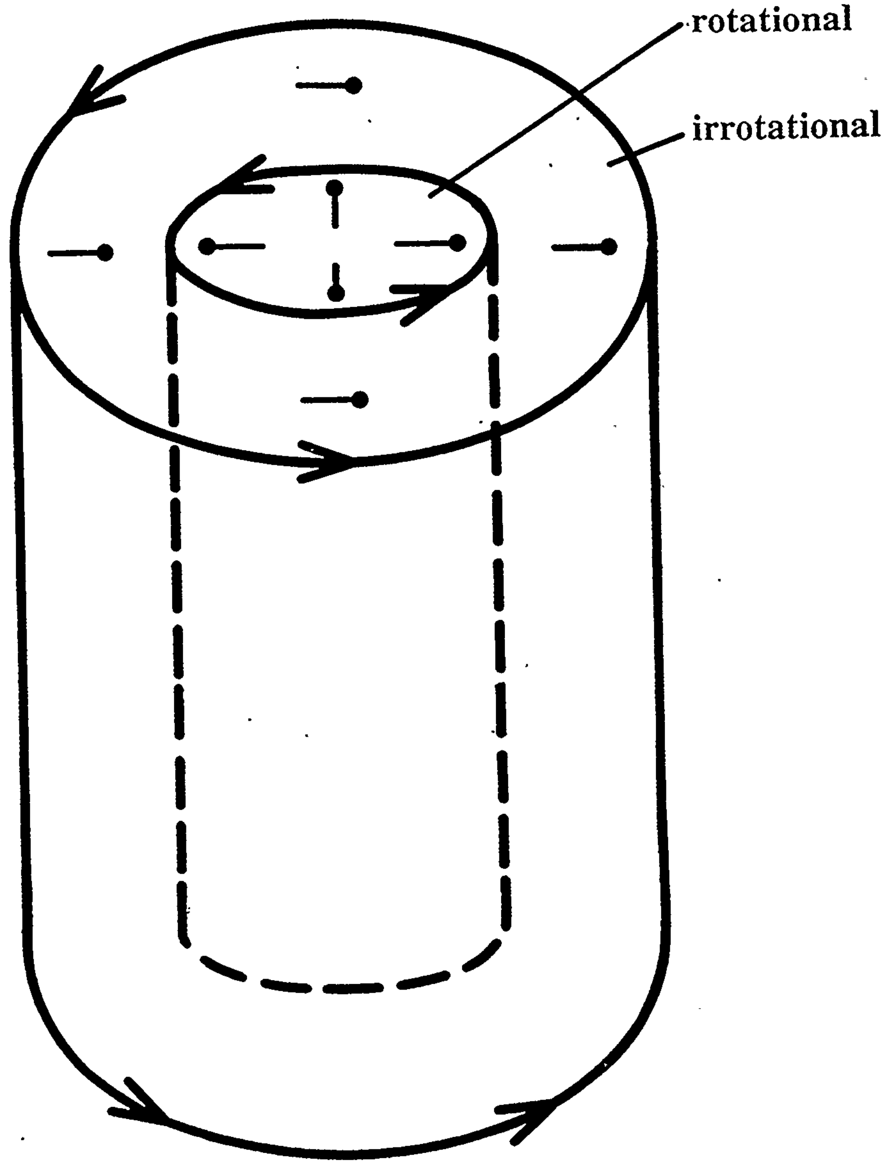
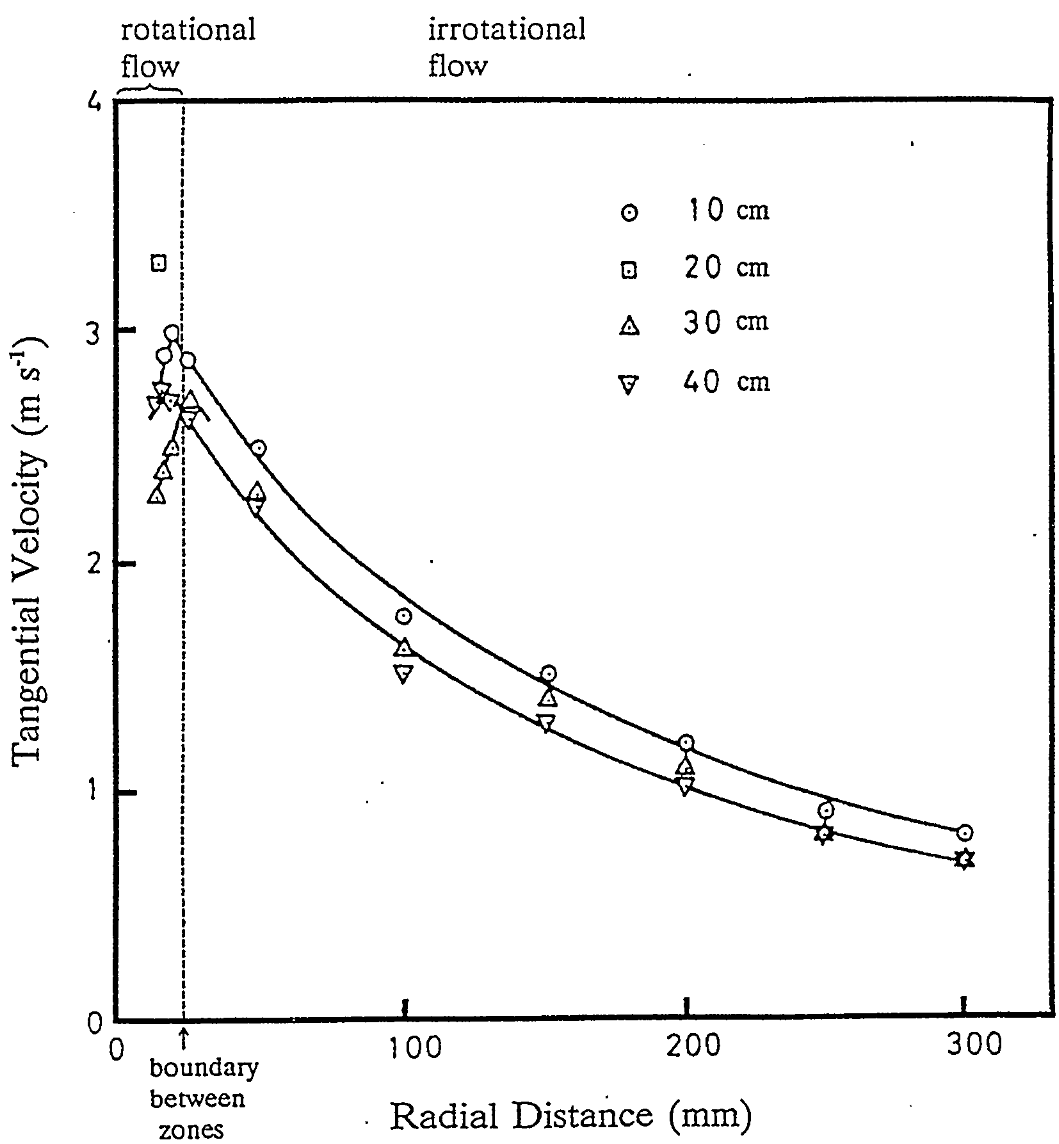

rotational
irrotational

Figure 4. The tangential velocity, U_t, distribution in a vortex (where $U_t = 2\pi f$, where f is frequency of rotation). Tangential velocity increases from the centre (radius = 0) of the vortex to the outer boundary of the rotational zone and then decreases through the zone of irrotational flow, following Chigier *et al.* (1970). The symbols represent different heights in the vortex at which tangential velocities were measured.


rotational flow
irrotational flow
Tangential Velocity (m s-1)
Radial Distance (mm)
boundary between zones
10 cm
20 cm
30 cm
40 cm
0
1
2
3
4
0
100
200
300

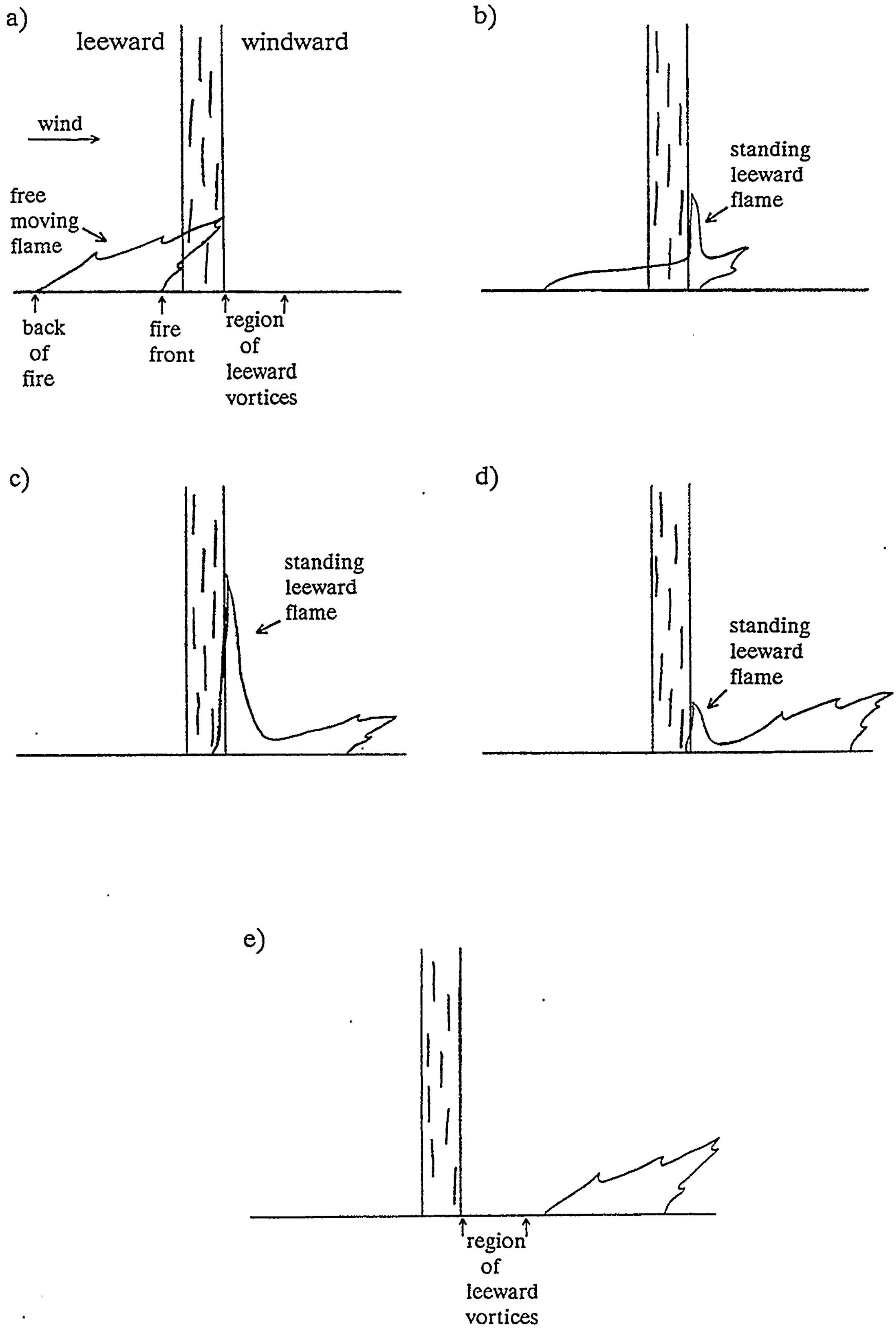
because the Reynolds number of the flame is greater than 3.5 x 10^6 ($Re_f = d_f U_f / \upsilon$, where d_f is the diameter of the flame and U_f is the vertical velocity of the fuel). A diffusion flame is one in which the gaseous fuel and oxygen are brought together by molecular and/or turbulent diffusion and combustion occurs along the visible flame boundary. Another type of flame, a premixed flame, is one in which the gaseous fuel and oxygen are mixed <u>before</u> combustion occurs. The combustion reaction involves the chemical decomposition of fuel by heating (called pyrolysis), followed by ignition.

A fire scar will form only on the leeward side of a tree because there is differential heating around the base of a tree when a free moving flame passes by the tree. Differential heating is a result of the leeward vortices increasing the residence time of the free moving flame on the tree's leeward side, compared to the residence time on the tree's windward side. The residence time, τ_f (sec), of a free moving diffusion flame on the windward side of a tree is a function of the depth of the flame, w (m), and its rate of spread, R (m/sec), and is given by

$$\tau_f = \frac{w}{R} \tag{2}$$

Figure 5 shows the passage of a free moving diffusion flame by a tree. As soon as the base of the flame reaches the centre of the periphery of the tree (Figure 5b), part of the flame is drawn up into the centres of the leeward vortices, producing a standing leeward flame. In effect, the flame depth is increased by a distance of one half tree diameter. The standing leeward flame increases in height as the free

Figure 5. A diagrammatic representation of what happens as a free moving diffusion flame passes by a tree. When the front (or back) of a free moving flame (a) reaches the centre of a tree, the flame increases in height on the leeward side of the tree, producing a standing leeward flame (b). The standing leeward flame increases in height as the flame passes by the tree (c) and then begins to decrease when only the trailing edge of the free moving diffusion flame is in the leeward vortices, up to one and a half tree diameters downstream of the tree (d). Once out of the vortices the standing leeward flame disappears (e).


a)
leeward
windward
wind
free moving flame
back of fire
fire front
region of leeward vortices
b)
standing leeward flame
c)
standing leeward flame
d)
standing leeward flame
e)
region of leeward vortices

moving flame passes by the tree (Figure 5c and 5d). It persists until the trailing end of the fire leaves the vortices on the leeward side of the tree (Figure 5e). In effect, the flame depth is increased by a distance of approximately one and a half tree diameters. In total, the flame depth is increased by a distance of two tree diameters when a free moving flame passes by a tree. Consequently, the residence time of the standing leeward flame is given by

$$\tau_l = \frac{w}{R} + \left(\frac{2d}{R}\right) \qquad (3)$$

where d is diameter (m) of the tree. The increase in depth of the free moving flame results in an increased residence time on the leeward side of the tree by a factor of 2d/R (hereafter called the leeward factor).

When the front of a free moving diffusion flame reaches the centre of the periphery of a tree, it is drawn horizontally into the tree's leeward vortices through the boundary layer along the ground. This horizontal draw is a result of the ground slowing down the rotational motion in the vortices, creating a radial pressure gradient in each vortex core. The lower pressure in the centre of each vortex core adds buoyancy to the core and pushes the gaseous fuel in the boundary layer toward the axis of each vortex. The gaseous fuel continues to add to the buoyancy as it burns, while rising in the vortex core (Emmons and Ying 1967).

The flame increases in height once it is in the vortex cores because the rotation of the gaseous fuel in and at the boundary of the vortex cores (see Figure 4) decreases the turbulent mixing of fuel and air (Emmons and Ying 1967). Turbulence is reduced because the centrifugal force in the zone of irrotational flow opposes the movement of gaseous fuel toward the axis of the vortex core by angular momentum. As a result, the buoyancy of the rising core is not rapidly decreased by mixing and therefore a large buoyant pressure difference is produced in the very high, relatively small diameter buoyant core. The rate of mixing with the air decreases in the standing leeward flame since the rotation restricts the entrainment of air from the surroundings into the vortex cores and results in a confinement of the flames within the vortex cores. The consequent delay in the rate of mixing between the ground fuel and surrounding air results in a considerable increase in flame length (Chigier *et al.* 1970). In effect, the flame length increases because the flow of gaseous fuel in the vortex cores is now greater than the rate of mixing with the surrounding air and hence there is a greater length along which combustion can take place (Emmons and Ying 1967, Chigier *et al.* 1970).

Differential heating around the base of a tree is also due to a higher temperature in the standing leeward flame compared to the free moving diffusion flame. The rotation of the fuel in the vortex cores increases the combustion rate of fuel and air. The temperature through the centre of the standing leeward flame is higher because the flames in the two leeward vortices radiate towards each other.

Heat Transfer from the Standing Leeward Flame

A fire scar is a result of partial cambial death at the base of a tree. Death in the cambium occurs when the heat flux from the standing leeward flame penetrates the bark and kills the cambium. It is assumed that heating of the leeward side of the tree is unidirectional, that is, the heat flux is from the leeward flame and not from heat penetrating the tree stem from the windward side of the tree. Further, because heating is only for a brief period (seconds to minutes) and the bark has low thermal conductivity, the time required for the stem to experience a temperature change will be a function of both the residence time of the flame and the thickness of the bark. After the flame is removed, the temperature in the cambium through the bark will decrease, as shown in Figure 6.

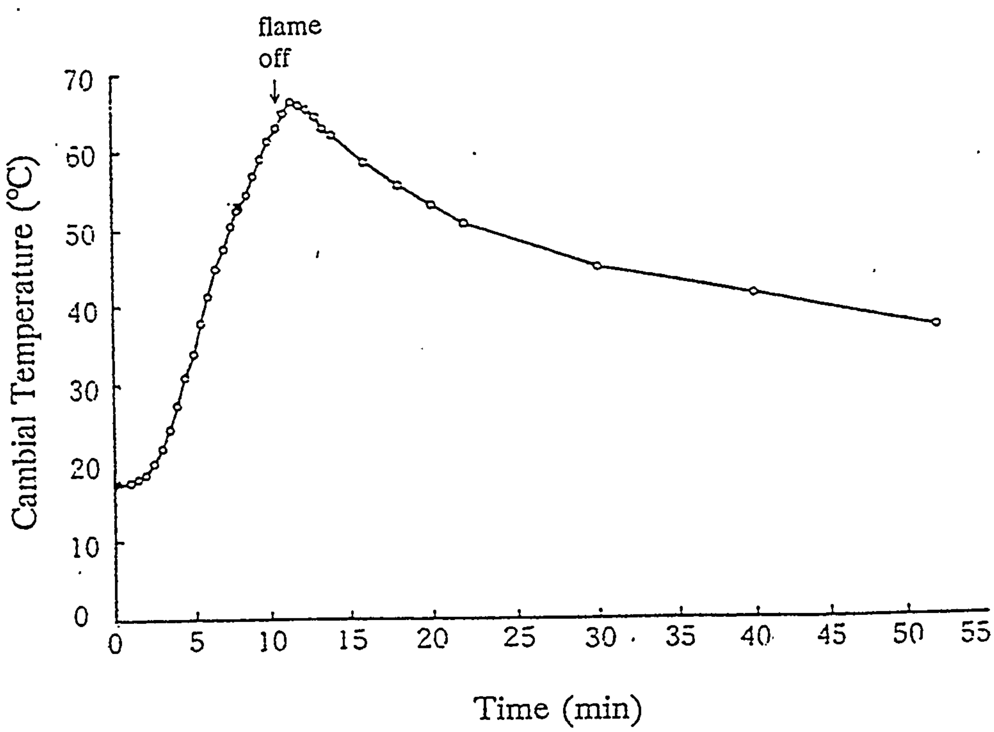
Results from this transient heating can be described by Fourier's Law of Conduction (Sucec 1985):

$$\frac{\partial^2 \theta}{\partial x^2} = \frac{1}{\alpha}\frac{\partial \theta}{\partial \tau} \qquad (4)$$

where the rate of change of the excess temperature ratio, θ, within the bark, x (m), is equal to the inverse of the thermal diffusivity, α (m^2/s), multiplied by the rate of change of the excess temperature ratio with respect to time τ (s). The excess temperature ratio is given by

$$\theta = \frac{T_c - T_f}{T_o - T_f}$$

Figure 6. Temperatures in the cambium through the bark as a constant heat source is applied to the outside of a tree and then removed, from Gill and Ashton (1968).


flame off
Cambial Temperature (°C)
0
10
20
30
40
50
60
70
0
5
10
15
20
25
30
35
40
45
50
55
Time (min)

where T_c is the lethal cambium temperature (°C), T_f is the temperature (°C) in the flame and T_o is the temperature (°C) of the cambium before heating occurs. Thermal diffusivity gives the rate at which temperature changes within the bark when its surface temperature changes. For equation 4, the following initial and boundary conditions were set:

1) at $x = 0$ and $\tau > 0$, $-h\theta = -k(\partial\theta/\partial x)$;

2) as $x \rightarrow \infty$ and $\tau > 0$, θ remains finite;

3) at $\tau = 0$ and $0 < x < \infty$, $\theta = \theta_o = T_o - T_f$,

where h is the surface coefficient of heat transfer (W/m^2 °C) and k is thermal conductivity (W/m °C). If we solve equation 4 according to the above conditions, we obtain the result for the excess temperature ratio of the bark. It is assumed that the bark: has a surface coefficient of heat transfer h; is initially at temperature T_o; and is then exposed to a flame of temperature T_f. This leads to the following equation:

$$\frac{\theta}{\theta_o} = \frac{T_c - T_f}{T_o - T_f} = erf\left(\frac{x}{2\sqrt{\alpha\tau}}\right) + \exp\left(\frac{hx}{k} + \frac{h^2\alpha\tau}{k^2}\right) \times \left[1 - erf\left(\frac{x}{2\sqrt{\alpha\tau}} + h\frac{\sqrt{\alpha\tau}}{k}\right)\right] \quad (5)$$

where erf is the Gaussian error function. Values of the error function, which defines the error associated with the excess temperature ratio, can be found in books with mathematical tables (*eg*. Abramowitz and Stegun 1964). Once the bark surface ($x = 0$) reaches the flame temperature, the surface coefficient of heat transfer approaches infinity ($h \rightarrow \infty$). This eliminates the terms to the right of $erf(x/2\sqrt{\alpha\tau})$, on the right hand side of the equation. Thus, the heat flux required to kill the cambium can be calculated using

$$\frac{T_c - T_f}{T_o - T_f} = erf\left(\frac{x}{2\sqrt{\alpha\tau}}\right). \tag{6}$$

In order to solve equation 6, the value of $(x/2\sqrt{\alpha\tau})$ must first be calculated. By knowing the lethal cambium temperature, T_c, temperature of the cambium before heating occurs, T_o, bark thickness, x, thermal diffusivity, α, and residence time, τ (calculated using equations 2 and 3), one can easily determine the flame temperature, T_f, required to kill the cambium. Conversely, by knowing T_c, T_f, T_o and α, one could similarly determine the residence time τ required to kill the cambium over a range of bark thickness. For example, if T_c = 60°C, T_f = 500°C, T_o = 20°C, α = 1.35 x 10^{-7} m^2/s and erf( ) = 0.917, then the residence time τ (sec), required to kill the cambium is given by

$$\tau = 1.24 \times 10^6 x^2 \tag{7}$$

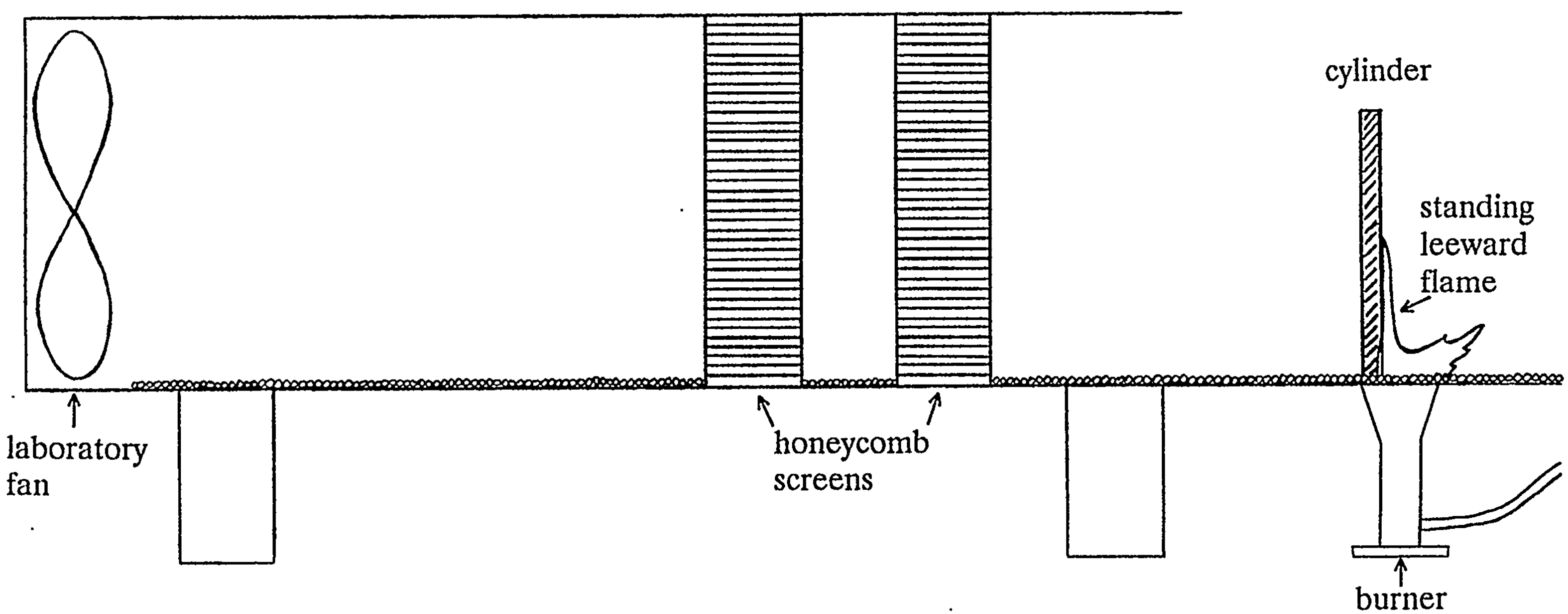
where the constant (1.24×10^6) is dependent on T_c, T_f, T_o and α. This is the same scaling value (*ie.* x^2 in equation 7) that was found empirically by Hare (1965b) and Vines (1968). By heating the bark on trees using various methods, and measuring the temperature reached on the bark surface and in the cambium, they observed that the time required to kill the cambium (*ie.* $T_c \geq$ 60°C (Kayll 1968)) was a function of the square of bark thickness. Given the above conditions, a tree with bark thickness, x = 0.01 m for example, would require a residence time, τ = 122 s, to kill the cambium.

METHODS

The mechanisms of partial cambial death were tested in a scaled down laboratory model (Figure 7), similar to that used by Gill (1974). The laboratory model is equivalent to tree boles in the field because the same air flow pattern can be obtained when the Reynolds number is the same. For example, a tree, 0.2 m in diameter, where the wind speed is 0.33 m/s (υ is held constant at 1.5×10^{-5} m^2/s) yields Re=440, a flow pattern of alternately shedding vortices. In the laboratory, this same flow pattern (Re=440) can be observed in a much smaller tree, 0.02 m, if the wind speed is increased to 3.3 m/s.

The laboratory set-up consisted of an open circuit, open jet, low speed wind tunnel, equipped with two honeycomb screens which acted to reduce the swirl and turbulence of the air created by the fan. The working section of the wind tunnel consisted of an asbestos bench with a burner fitted through the bench such that the burning surface and bench top were part of the same plane. The flame through the burner was turbulent ($Re_f > 3.5 \times 10^6$, where d_f is diameter of the burner and U_f is vertical velocity of the gas). The surface was roughened by placing small pea-sized gravel from the fan through to the working section. Metal cylinders, 0.95 cm, 1.25 cm and 1.9 cm in diameter, were used to simulate tree boles. The wind speed was regulated by a rheostat transformer and measured in the working section using a Datametrics 100 VT air flow meter and hot wire anemometer. Wind speed was

Figure 7. The laboratory set-up, including a wind tunnel equipped with a laboratory fan, diffusion flame and cylinder, used to simulate the passage of a free moving diffusion flame by a tree.


cylinder
standing
leeward
flame
laboratory
fan
honeycomb
screens
burner

measured at 1 cm intervals of height from the burner mouth. The wind tunnel was found to have a logarithmic wind profile similar to that found under a forest canopy (Albini and Baughman 1979). The length of the wind tunnel allowed a steady state wind profile to develop. For a steady state wind profile, the length of the wind tunnel was 200x the height of the surface roughness element (Monteith 1975). Wind speed at 1 cm above the surface was used to calculate the Reynolds number for flows around the cylinder.

To determine whether the points of flow separation correspond to the outer edges of a fire scar at the base of a tree, 242 discs were cut from fire scarred trees. The angle from the centre of the windward side of the tree to the outer edge of the killed area were measured on discs taken from fire scarred *Pinus banksiana* Lamb. from Prince Alberta National Park, Saskatchewan. Notice that angles were measured on discs from fire scarred trees since the entire killed area (especially the outer edges) are usually not visible from an intact tree.

To determine the difference in temperature between a free moving diffusion flame and a standing leeward flame, the vertical temperature profile of each flame type was measured using an Omega 872A digital thermometer with Omega chromel alumel bare wire thermocouples and NMP miniature sized connectors. The thermocouple wire was 1 mm in diameter and 31 cm in length and was encased in a ceramic tube for insulation. The temperature of the flame was measured at the centre, starting at the base and for every 1 cm in height. Re-radiation from the metal cylinder into the standing leeward flame was found to be negligible since temperature measurement was done before sufficient heating occurred. The temperature within the standing leeward flame was measured through the centre, 4 mm (horizontally) from centre, 8 mm from centre and 10 mm from centre, approximately 2 mm from the cylinder wall.

RESULTS AND DISCUSSION

The width of a fire scar at the base of a tree should be determined by the angle of separation of flow on the leeward side of a tree. This was established by comparing the theoretical angles of flow separation (82° when Re < 3×10^5 and 110° when Re > 3.5×10^6 (Potter and Foss 1975)) to the angle to the edge of the killed area on fire scarred trees in the field (Figure 8).

Figure 9 shows a frequency distribution of angles from the centre of the windward side of the tree (see Figure 2b) to the outer edge of the killed area on 242 fire scarred *Pinus banksiana*. The distribution of angles appears to be bimodal, with the two modes at 85°-95° and 115°-125°. The theoretical angles of separation (82° in a laminar boundary layer and 110° in a turbulent boundary layer) do not fall exactly within the peaks of the two modes, rather the peaks are at slightly larger angles. This shift is not too surprising since we would expect the scar to extend, at most, to

Figure 8: A diagram of a fire scarred tree disc showing how the angle from the front and centre of the tree to the outer edge of the fire scar was measured on trees from the field.

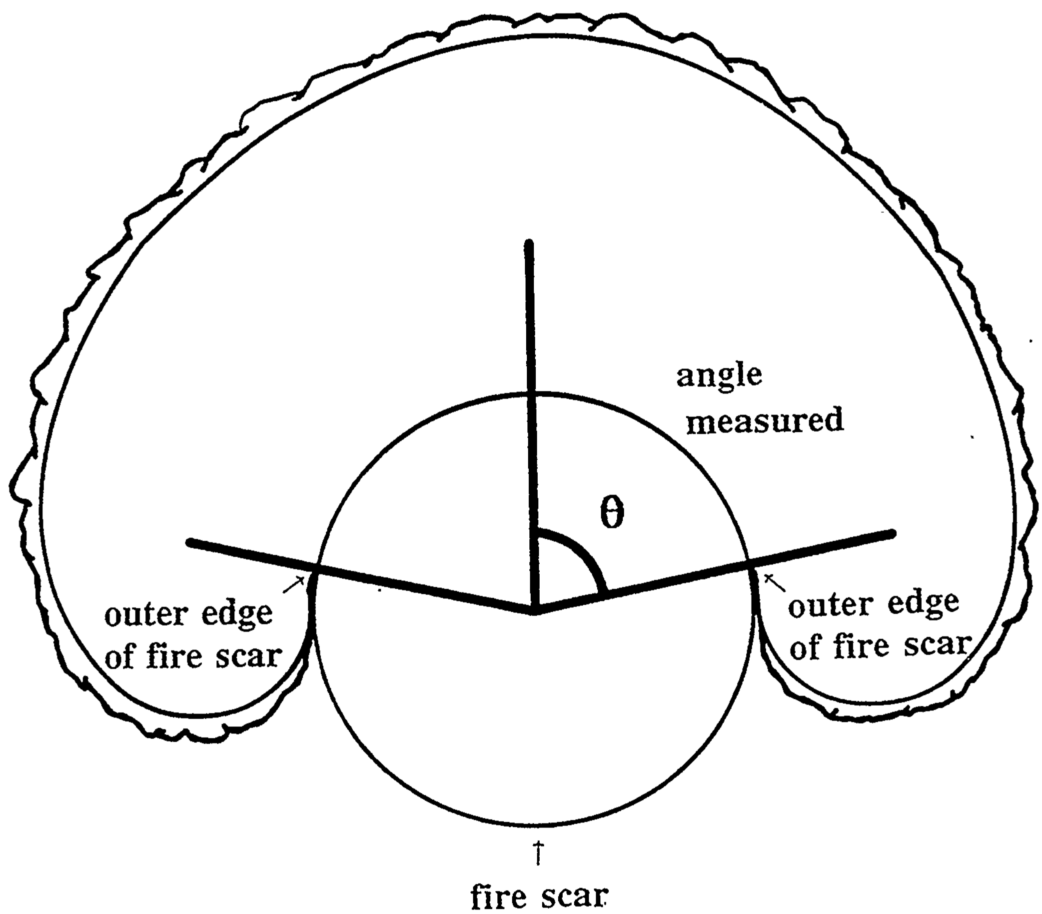
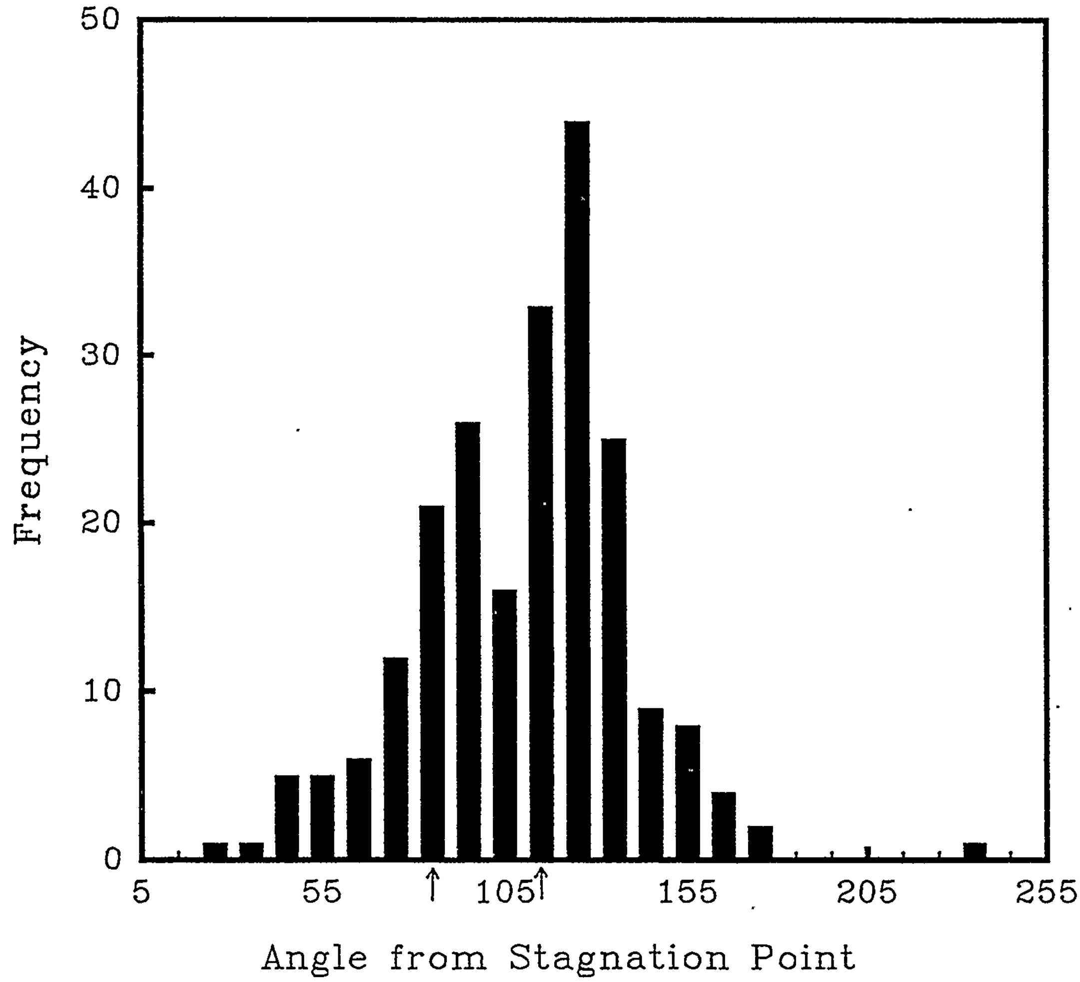

angle
measured
θ
outer edge
of fire scar
outer edge
of fire scar
fire scar

Figure 9. Measures of the angle from the centre of the windward side of the tree to the outer edge of the fire scar on 242 fire scarred *Pinus banksiana* from Prince Albert National Park, Saskatchewan. The arrows indicate the theoretical angles of separation in a laminar (82°) and turbulent (110°) boundary layer.


50
40
30
20
10
0
Frequency
5
55
105
155
205
255
Angle from Stagnation Point

the position of the separation points, since the leeward flame is killing the cambium. The spread around these two peaks seems to be a result of slight differences in the height at which angles were measured on the tree.

The occurrence of fire scars on the leeward side of a tree is a result of the heat flux from the standing leeward flame penetrating the bark and killing the cambium. Fire scars form on the leeward side of a tree but not on the windward side because: 1) the residence time of the standing leeward flame is longer than the residence time of the free moving flame on the windward side of a tree; and 2) the temperature in the standing leeward flame is greater than in the free moving diffusion flame.

The increase in residence time on the leeward side of a tree leads to differential heating around the base of a tree. In order to show this differential heating the critical flame temperature required to kill the cambium on the windward and leeward sides of a tree were plotted (see axes on Figure 10). The critical temperature required to kill the cambium was calculated using equation 7 over a range of bark thickness[1] (0.004 - 0.03 m). For each bark thickness, the critical flame temperature, T_f, required to kill the cambium was calculated using thermal diffusivity $\alpha = 1.35$ x

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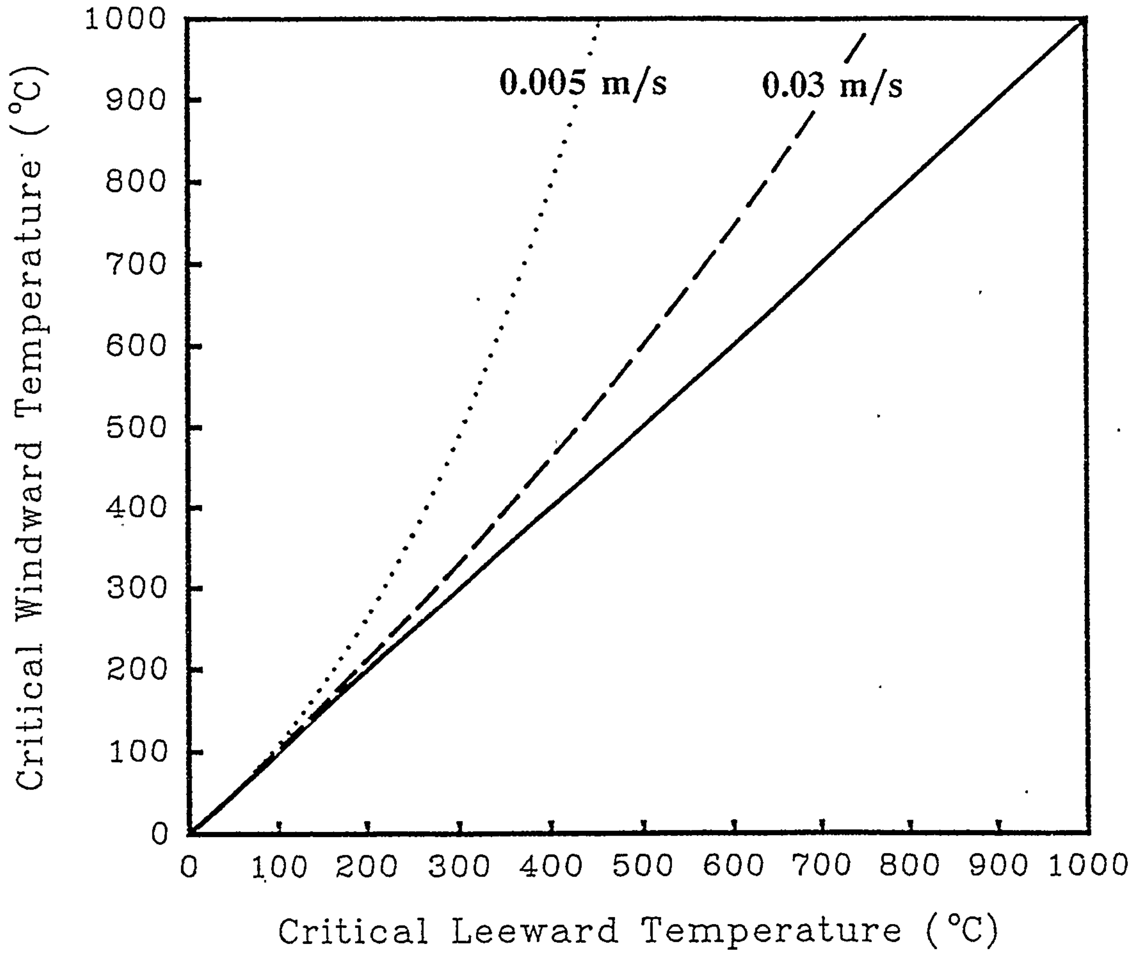
[1]Equation 7 was solved for both the windward and leeward sides of a tree, over a range of bark thickness, to see how the critical temperature to cambial kill changes as bark thickness increases. Since tree diameter increases with an increase in bark thickness (*eg.* $x = 0.037d + 0.004$ for *Pinus banksiana*), the effect of an increasing tree diameter on the leeward residence time could also be determined (see equation 3).

Figure 10. The critical temperatures for cambial kill were calculated using equation 7 (see text for explanation). Differential heating increases with a decrease in the rate of spread, except where tree diameter is very small.


0.005 m/s
0.03 m/s
Critical Windward Temperature (°C)
Critical Leeward Temperature (°C)
0
100
200
300
400
500
600
700
800
900
1000

10^{-7} m^2/sec (Spalt and Reifsnyder 1962), temperature of the cambium before heating, T_o =20°C, and lethal cambium temperature, T_c = 60°C. The residence time τ on the windward and leeward sides were calculated using equations 2 and 3 respectively, where depth of the flame was held constant at 2 m.

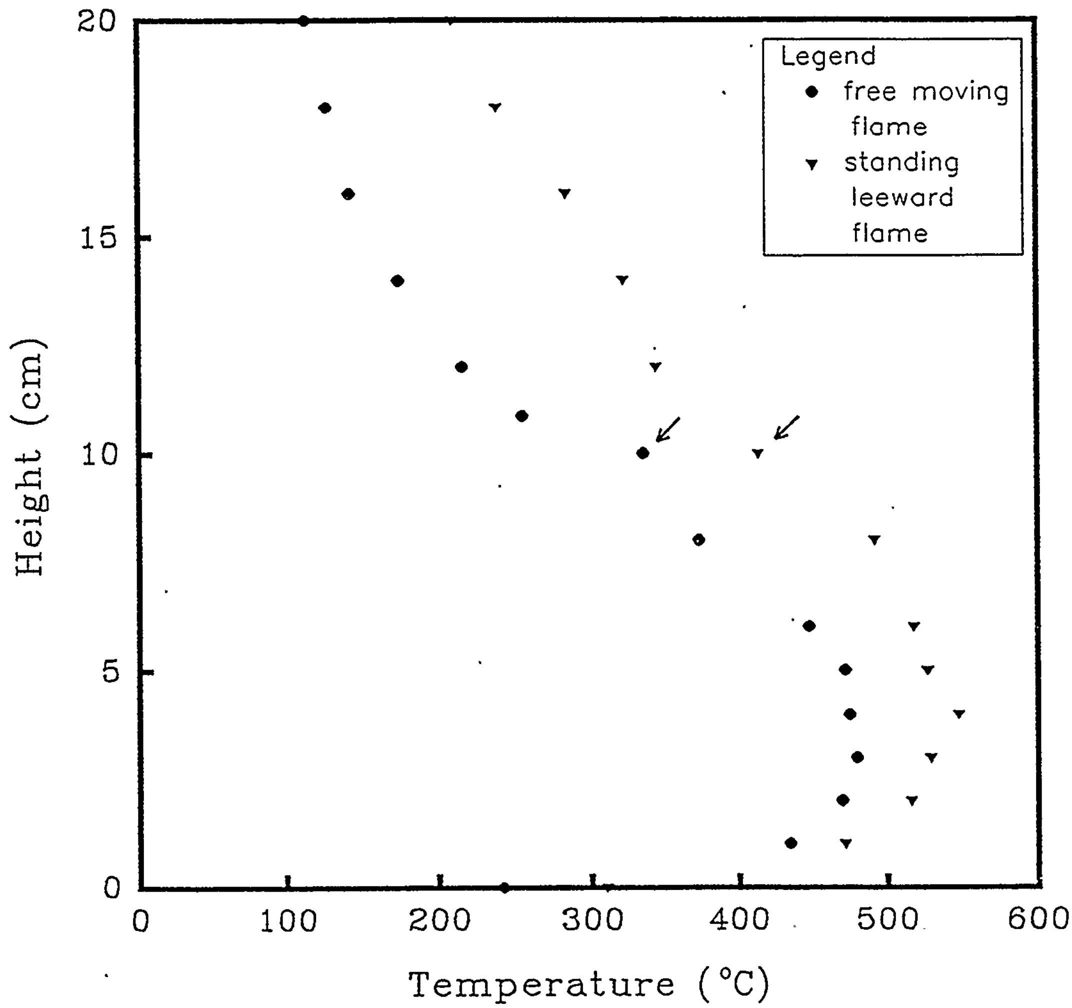
In Figure 10, where slope = 1, the temperature required to kill the cambium is the same on the windward and leeward sides of the tree (*ie.* there is no differential heating). This occurs when the rate of spread of the fire is very fast (residence time very low), regardless of the tree diameter. Examination of the leeward factor (2d/R) in equation 3 shows that a very high rate of spread will result in a very low leeward factor such that the increase in leeward residence time over the windward residence time becomes negligible, no matter how large the tree diameter. In effect, both the leeward and windward sides have the same residence times when the rate of spread is very fast.

In Figure 10, where slope > 1, the temperature required to kill the cambium becomes higher for the windward side compared to the leeward side (*ie.* there is differential heating). This occurs when the rate of spread becomes slower than it is at slope = 1. As the rate of spread decreases further, differential heating increases, resulting in a steeper slope. Examination of equation 3 shows that as the rate of spread decreases, the leeward factor increases, causing a significantly greater leeward residence time compared to the windward residence time. Notice that the slope of the curve will never be less than one since the windward residence time will never be greater than the leeward residence time. In other words, the windward temperature will always have to be the same or higher than the leeward temperature in order to kill the cambium on the windward side of a tree.

Why do the lines in Figure 10, representing different rates of spread, converge at lower critical temperatures? Examination of equation 3 shows that small diameter trees will not significantly increase the residence time of the leeward flame and so the critical temperature to cambial kill will be almost the same on both the windward and leeward sides of the tree. Thus, if the flame temperature is high enough to kill the cambium on the leeward side of the tree, then the cambium on the windward side of the tree will also be killed. This will result in complete cambial kill around the base of the tree and rapid tree mortality. This seems likely to occur since small diameter trees also have thin bark. Consequently, it appears that we rarely see fire scars on small trees because their cambium is usually completely killed around the base of the tree which results in tree mortality. In addition to this explanation, Appendix 1 shows that small trees have crowns that are typically close to the ground such that even low intensity fires will cause tree mortality from crown scorch.

In addition to an increased residence time of the standing leeward flame, the temperature in the standing leeward flame is higher than the free moving diffusion flame. Figure 11 shows the one dimensional vertical temperature, measured through

Figure 11. The vertical temperature distribution in a standing leeward flame compared to the free moving diffusion flame of the same height. The arrows indicate the average height of the flames.

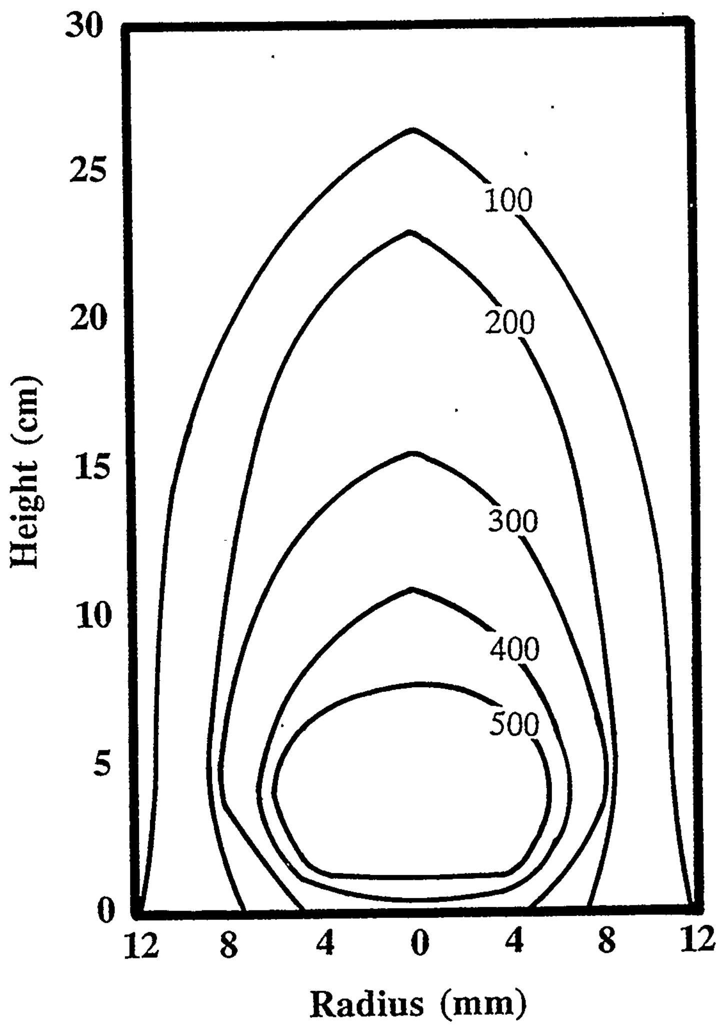


Legend
free moving flame
standing leeward flame
Height (cm)
Temperature (°C)
0
5
10
15
20
0
100
200
300
400
500
600

the centre of a standing leeward flame, compared to a diffusion flame of the same height. In both the leeward flame and free moving diffusion flame, temperature increases from the base of the flame and reaches a maximum at a height approximately 40% of the height of the flame, and then decreases with a further increase in height. At all heights the standing leeward flame is higher in temperature than the diffusion flame. The increase in temperature in the standing leeward flame is due to an increase in the burning rate of fuel and air in the vortex cores (Emmons and Ying 1967). The mechanism responsible for this increased rate of combustion has not yet been studied and is beyond the scope of this paper.

Why is the cambium often killed in a triangle shape? Figure 12 shows the two dimensional temperature distribution of the standing leeward flame in Figure 11. The temperature is highest at the centre of the flame, at a height approximately 40% of the height of the flame. Temperature decreases toward the sides and top, with isotherms approximating a triangular shape. Notice that the temperature is not higher through the centre of the vortices (±4 mm radius), as may first be expected. Rather, the temperature is highest through the centre of the flame, between the two vortices. As shown by Emmons and Ying (1967), inside each vortex is a cool fuel rich core which burns as it rises from the ground surface. The highest flame temperatures occur at the vortex boundaries, where the rate of combustion is greatest. It appears that the heat from the flame boundaries in both vortices radiate towards each other, increasing the temperature in the centre of the flame. The outer

Figure 12. The two dimensional temperature distribution within the standing leeward flame shown in Figure 11. The innermost isotherm, 500°C, for example, encompasses all regions that are 500°C or higher. The temperature is highest at the centre of the flame, at a height approximately 40% of the height of the flame. Temperature decreases toward the sides and top. Notice the triangular shape of the isotherm for 200°C.


30
25
20
15
10
5
0
Height (cm)
100
200
300
400
500
12
8
4
0
4
8
12
Radius (mm)

edges of the flame do not experience the same increase in temperature because of the cooling effect of the surrounding air.

CONCLUSIONS

The causal mechanisms have been given for four key observations associated with fire scar formation on trees. It is interesting that the present explanation uses largely existing understandings. Despite some excellent attempts at determining how fire scars form on trees, there has been some difficulty in determining how fires cause this ecological effect. Critical to determining the mechanisms was having a clear understanding of: the formation of vortices on the leeward side of a tree; the interaction of rotational and irrotational motion in a vortex which suppresses turbulence and produces a standing leeward flame; and the heat transfer from the standing leeward flame which kills the cambium. It is clear from this explanation that much of the folklore surrounding fire scar formation can now be addressed. Trees survive fire and have fire scars because there is differential heating around the base of a tree. The cambium is not completely killed because, in most cases, the residence time and temperature is high enough only on the leeward side of the tree.

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APPENDIX 1.

Fire scars are rarely found on small trees because their cambium is completely killed around the base of a tree and/or their crowns are typically near the ground, such that their foliage is often killed by crown scorch. A well established relation (cf.Thomas 1963)[1] shows that the temperature reached at any height, h_t (m), above a fire depends on the fire intensity, I (kW/m) and the ambient temperature T_o (°C):

$$h_t \alpha \frac{I^{2/3}}{T_o}$$

Using this relation, and empirical measures, Van Wagner (1973)[2] found that the height of crown scorch, where the temperature of foliage kill is $T_c \geq 60$°C, is given by

$$h_s = 0.09196\ I^{2/3}$$

A tree 5 m in height, for example, would only require a fire intensity of I = 122 kW/m to completely kill its crown. This corresponds to a flame height of 0.6 m. As the height of a tree increases, a greater proportion of the foliage is likely to be above the height of lethal scorching. Clearly, there is some

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[1]Thomas, P.H. 1963. The size of flames from natural fires. Proceedings of the Ninth (International) Symposium on Combustion. William and Wilkin. 844-859 pp.

[2]Van Wagner, C.E. 1973. Height of crown scorch in forest fires. Canadian Journal of Forest Research 3: 373-378.

interaction between cambial and canopy mortality that will result in overall tree mortality, however at present, this interaction is poorly understood.