Thermally induced bark swelling in four North American tree species

B.W. Butler, B.W. Webb, D. Jimenez, J.A. Reardon, and J.L. Jones

Abstract: Bark protects both the living phloem and the vascular cambium of trees. For some tree species the bark has been observed to swell in the radial direction when heated by nearby flames, possibly providing additional protection from thermal injury. In this study, detailed measurements of bark swelling (tumescence) are reported for four species: Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), chestnut oak (*Quercus prinus* L.), and red maple (*Acer rubrum* L.). Tests were conducted on over 574 samples extracted from 44 separate trees. The results clearly show that bark swelling occurs in the mature bark of Douglas-fir and to a lesser degree in chestnut oak. Ponderosa pine and red maple did not exhibit statistically significant swelling, but rather a modest decrease in overall bark thickness with heating. Significant swelling in Douglas-fir bark began at approximately 125 °C and resulted in a 15%–80% increase in overall bark thickness. Swelling of chestnut oak was observed to begin at an average temperature of 225 °C and resulted in a 5%–10% increase in total bark thickness. The increase in bark thickness occurred primarily in the radial direction in mature bark.

Résumé : L'écorce protège à la fois le phloème vivant et le cambium chez les arbres. Chez certaines espèces d'arbres, on a observé que l'écorce se gonfle dans la direction radiale lorsqu'elle est chauffée par les flammes, ce qui procure possiblement une protection additionnelle contre les blessures causées par la chaleur. Dans cette étude, les auteurs présentent des mesures détaillées du gonflement (tumescence) de l'écorce chez quatre espèces : le douglas (*Pseudotsuga menziesii* (Mirb.) Franco), le pin ponderosa (*Pinus ponderosa* Dougl. ex. Laws.), le chêne de montagne (*Quercus prinus* L.) et l'érable rouge (*Acer rubrum* L.). Des tests ont été réalisés sur plus de 574 échantillons prélevés sur 44 arbres différents. Les résultats montrent clairement que le gonflement de l'écorce se produit dans l'écorce mature du douglas et à un moindre degré dans celle du chêne de montagne. Le pin ponderosa et l'érable rouge n'ont pas montré de renflement statistiquement significatif, mais plutôt une légère diminution de l'épaisseur globale de l'écorce qui avait été chauffée. L'écorce du douglas a commencé à gonfler de façon significative à environ 125 °C produisant une augmentation de 15 % à 80 % de l'épaisseur globale de l'écorce. Chez le chêne de montagne, le gonflement a commencé à se manifester à une température moyenne de 225 °C et s'est traduit par une augmentation de 5 % à 10 % de l'épaisseur totale de l'écorce. Dans l'écorce mature, l'augmentation de l'épaisseur de l'écorce s'est produite principalement dans la direction radiale.

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Introduction

Tree survival or mortality as a function of species and age is often one of the management objectives of prescribed and natural fire (Greene and Shilling 1987). Fires burning near tree stems can result in a sufficient temperature rise in the vascular cambium to cause injury and death of the living tissue, and, if sufficiently widespread, death of the entire tree (Peterson and Ryan 1986; Durcey et al. 1996; Dickinson and Johnson 2001). Generally, stems with thicker bark experience slower heating and lower temperature rise in the vascular cambium when exposed to external heating. This is supported by experiment (Ryan and Reinhardt 1988; van Mantgem and

Schwartz 2003). In a recent study directed at the development and experimental evaluation of a model for predicting the timewise temperature distribution through a living plant stem under heating conditions (Jones et al. 2004), it was observed that the exterior surface of the bark of some species swelled when heated, resulting in an increase in the overall bark thickness and stem diameter. Measurements indicate that the swollen portion of the bark exhibits a decrease in bulk density. Bulk density correlates with thermal conductivity (Incropera and DeWitt 2002). Lower thermal conductivity and increased bark thickness increases the resistance of the bark layer to energy transfer (Loomis 1973; Harmon 1984; Ryan and Steele 1989; Schoonenberg et al. 2003). The result is lower vascular cambium temperatures. Jones et al. (2004) have shown that bark swelling is significant for at least one tree species when considering heat transfer through tree stems and that accurate predictions of cambial temperature require increased understanding of thermally induced bark swelling.

Detailed information exists on plant stem and bark physiology (Ross 1966; Howard 1971; Simpson and TenWolde 1999; Armstrong 2001). Bark has been defined as a moderately porous matrix whose thermal properties are dependent

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Table 1. Summary of experimental tests conducted to characterize bark swelling.

Species	No. of trees sampled	Total no. of tests	Diameter range (cm)
Douglas-fir (*Pseudotsuga menziesii*)	27	375	3.8–107.0
Ponderosa pine (*Pinus ponderosa*)	4	42	4.9–13.1
Red maple (*Acer rubrum*)	5	37	4.9–12.5
Chestnut oak (*Quercus prinus*)	8	120	6.8–26.1

on moisture content and temperature (Martin and Crist 1968; Vines 1968; Hengst and Dawson 1994). Only limited work has focused on determining the physical properties of bark (Lamb and Marden 1968), its temperature dependence, and the distribution of moisture in bark (Martin 1963*a*, 1963*b*, 1967; Litvay and McKimmy 1975; Greene and Shilling 1987). It is recognized that energy is required to pyrolize (drive volatile gases from the solid material under heating conditions) the hydrocarbons in the bark and wood and that this process constitutes significant energy absorption (Spalt and Reifsnyder 1962; Lee and Diehl 1981; Tillman et al. 1981; Susott 1982). All of this information is critical to accurate understanding and modeling of the temporal response of a tree stem to a time-varying external heat source (Jones et al. 2004).

It is generally recognized that fire changes the appearance and the structure of tree bark and that visible damage to the exterior surface of the stem can indicate potential damage to living tissues within the plant stem. However, the authors of this study found no prior work focused on characterizing the phenomenon of bark swelling (alternately referred to as tumescence) as a result of heating and the impact that thermally induced bark swelling may have on cambial temperature history.

The objective of this work is to characterize through experimental measurement the thermally induced swelling exhibited by the bark of four tree species, and to identify the mechanisms for such swelling, if it occurs. It is hoped that this study will provide some understanding of the swelling phenomenon, and quantify the swelling behavior in these species. Such information will enhance current understanding of tree physiology and species-specific adaptations to fire. Models based on increased understanding and knowledge hold the promise of more accurately predicting fire-induced tree stem survival and mortality. When used in a decision support role, such models can significantly improve land managers' abilities to effectively achieve their management objectives.

Materials and methods

Four species were selected for this study: Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws.), chestnut oak (*Quercus prinus* L.), and red maple (*Acer rubrum* L.). These species were selected as being somewhat representative of North American conifer and hardwood species. Further, they were the subject of a previous work that focused on the development of a model for predicting fire-induced stem heating (Jones 2003; Jones et al. 2004). Initially, the study focused on small to moderate stem diameters that are often targeted in management efforts to control understory species and rangeland encroachment. Laboratory and field burning experiments were conducted on 574 samples extracted from 44 separate trees

over a range of tree diameters (Table 1). Diameters reported for the laboratory tests represent the diameter of each individual cross-section sample. Preburn diameters for the field tests were recorded at heights above ground level, where maximum bark surface temperatures were expected based on the heating technique that was used.

Tree stem samples were harvested from whole trees. Douglas-fir and ponderosa pine were collected during the late fall and spring from Patty Canyon, Blue Mountain Recreational Area, and Lubrecht Experimental Forest, all located within 20 km of Missoula, Montana (46°55′N, 114°5′W, elevation 977 m). Red maple and chestnut oak samples were collected during the late fall and spring from the Vinton Furnace Experimental Forest located near Athens, Ohio (39°20′N, 82°6′W, elevation 700 m).

A series of laboratory experiments was conducted to identify which tree species displayed bark swelling when heated. Samples were cut from various positions along the main stem. The main stem was divided into physically manageable stem samples that were wrapped in plastic and placed in cold storage. Cross-section samples approximately 3 cm thick were taken from the prepared main stem samples. Prior to cutting the 3 cm thick sample cross-sections, segments of 5 cm nominal length were cut from both ends of the prepared main stem samples to reduce the drying effects associated with exposed cut ends. Unless stated otherwise, tests were conducted within 6 d of felling the tree.

All bark thickness measurements were made using a set of calipers calibrated to 0.01 mm. However, because of the irregularity in the bark section surface and uncertainty in the exact measurement location, the pre- and post-heating bark thickness measurements are estimated to be accurate to approximately 0.5 mm.

Stem diameter was measured along two mutually perpendicular diametral lines on each stem slice using a set of calipers. Bark thickness at each location was also measured and recorded. It is recognized that with the irregular plate–fissure bark morphology of some species, there is inherent uncertainty in this characterization of both stem diameter and bark thickness.

Initial experiments were conducted on cross-section samples. Heat treatments were applied at measurement points established on the bark surface at points 90° apart. The measurement point was heated either by a hot air gun or propane torch until the onset of surface charring. Bark thickness was then remeasured at the same locations as the preheating measurement.

A second set of laboratory experiments focused on the swelling of small samples of mature Douglas-fir and chestnut oak bark nominally 1 cm × 1 cm × 2 cm long (long dimension along radial direction of stem) as a function of the time that the sample was exposed to a constant temperature. These experiments provided more detailed information about the

bark swelling – temperature relationship. The samples for these tests were cut from sections (>5 cm thick) of mature bark. Ten to 15 samples were placed in a constant temperature oven, and the change in the radial (long) dimension was recorded at 10-min intervals. Measurements were continued for 60–70 min. These experiments were performed for oven temperatures of 100, 125, 150, 200, 250, 300, and 400 °C for the Douglas-fir and 100, 150, 200, 250, 315, and 360 °C for the chestnut oak. The data for the 250, 300, and 400 °C Douglas-fir tests were truncated after the samples began actively burning. Data reported herein represent the average of a minimum of 10 sample measurements at each oven temperature condition.

A third set of laboratory experiments examined the relationship between moisture content and swelling in Douglas-fir and chestnut oak. Separate testing was conducted on nominally 1 cm × 1 cm × 2 cm (along stem radial direction) bark samples cut from freshly harvested stem sections. These samples were immediately placed in a 250 °C oven for 20 min. The change in dimension (corresponding with the radial axis of the stem) was recorded. A second sample set from the stem sections was dried in a dry atmosphere at 95 °C for 14 d. The dried samples were then exposed to heating in the 250 °C oven, and the resulting swelling was measured. Differences in observed swelling between the freshly cut and dried samples were then attributed to differences in initial moisture content.

In addition to the laboratory experiments, a series of field experiments were conducted on live standing trees. The amount of swelling was measured using three different methods: (*i*) a measuring tape calibrated to diameter, (*ii*) a bark thickness increment bore, and (*iii*) by recording the change in exposed length of a steel nail that had been driven through the bark into the sapwood.

The diameter tape method consisted of simply measuring the circumference of the stem both before and after heating with a measurement tape calibrated to diameter instead of length. Because this technique measures only the change in diameter, it requires an independent measurement of the initial bark thickness. The change in tree stem diameter correlates with an average change in bark thickness around the periphery of the stem. This method proved problematic, because the tape tended to damage the fragile swollen and charred bark and, further, only average swelling information for the stem perimeter was provided.

The bark thickness increment bore method consisted of inserting an increment bore gauge through the bark until it reached the sapwood. Postheating bark thickness was measured in the same manner. This method also proved unreliable, as the swelled and charred bark is fragile and thus susceptible to damage during the boring process.

For this study the preferred method of bark thickness measurement for in situ experiments on live trees consisted of driving steel nails (approximately 1.5 mm in diameter × 60 mm long) through the bark into the sapwood. The nails were sufficiently long to penetrate the bark and reach firmly into the sapwood. Nominally 1–2 cm of the nail was left exposed outside the bark surface. The exposed length of the nail was then measured with machinist calipers calibrated to 0.01 mm. This measurement was made before and after heating. The difference between the exposed length before and after heating is the change in local bark thickness. Measurements on

the same stem at multiple circumferential locations were made with an emphasis on characterization of swelling at the plates (rather than fissures).

The heating method for the field measurements was adapted from work by Russell and Dawson (1993), and consisted of affixing a kerosene-soaked cotton rope to the stem approximately 15 cm below the measurement location. The rope was cut to a length equal to the stem circumference, wrapped around the stem, and the ends of the rope were secured with wire. The rope was then ignited, and the kerosene combustion provided the heat source. The rope diameter selected determined the burn duration; larger diameters provided longer burn times. The time-resolved heat flux was measured using calibrated heat flux sensors embedded in the stem, and positioned flush with the bark surface adjacent to the bark swelling measurement location. This heating method resulted in 8–15 min of heating with typical average and maximum heat flux levels incident on the surface of the bark of 40 and 80 kW·m^{-2}, respectively. These heating rates were similar in magnitude and duration to those reported by others for surface fires burning in natural fuels (Hengst and Dawson 1994).

The dependence of bark swelling on initial bark thickness was characterized by applying a locally linear LOESS regression technique to the data (Cleveland and Grosse 1991). Confidence intervals (95%) were also calculated above and below the LOESS regression, and are presented with the regression. Since there is a nearly linear relationship between bark thickness and stem diameter for mature samples, these swelling data could also have been presented as a function of initial stem diameter (Hengst and Dawson 1994; Reinhardt et al. 1997; Lutes 2001).

Results and discussion

In the following sections, the swelling response of each species to heating is discussed in sequence. For those species that exhibited significant swelling, some measurements of the temperature corresponding with the onset of swelling, the dependence of swelling on tissue type, and the effect of moisture on swelling are presented and discussed as well.

Douglas-fir

The heating-induced change in bark thickness is presented for Douglas-fir as a function of initial bark thickness (Fig. 1). Samples were collected from stems with diameters ranging from 3.8 to 107.0 cm, which corresponded with a bark thickness range of 1–106 mm. There is significant scatter in the experimental data, which arises from the combination of measurement technique and the inherent variability in Douglas-fir bark morphology. The data for Douglas-fir bark suggest that swelling is dependent on bark structure and age. For the purposes of this study, smooth bark is termed juvenile and is generally found on stems with total bark thickness less than approximately 10 mm. As the total thickness exceeds 10 mm, the bark transitions from the smooth, relatively thin surface to the plate–fissure structure found on mature bark. The data reveal that juvenile stems (characterized by smooth, relatively thin bark) exhibit either swelling or shrinkage, and no clear trend is revealed by the regression (Fig. 1). This is attributed to variability in the stem diameter at which the bark transitions from the smooth, nonswelling juvenile bark to

Fig. 1. In situ swelling response in Douglas-fir (*Pseudotsuga menziesii*). The swelling data are normalized by the original bark thickness.
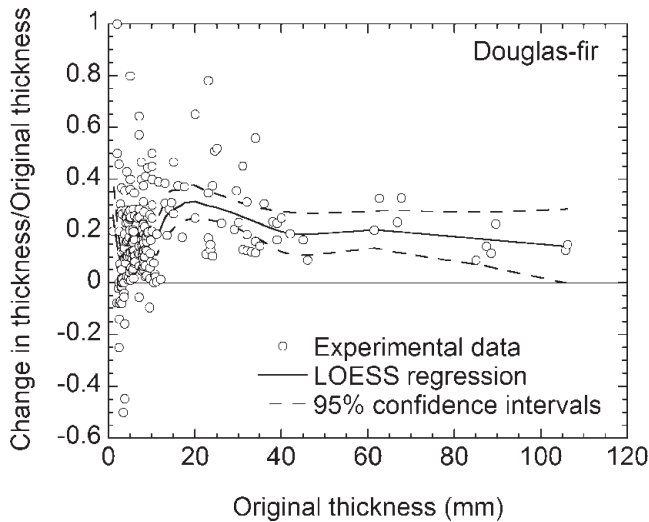
mature bark. As bark thickness exceeds 10 mm, thermally induced swelling is the only response observed. For mature bark (i.e., thickness >10 mm) the increase in overall bark thickness is greatest (i.e., approximately 30% increase over the original bark thickness) for nominally 20-mm-thick bark. As bark thickness increases above 20 mm, swelling gradually decreases to a nominal value of 20% (over the range of data presented here). Intuitively, it may be anticipated that this value will continue to decrease for thicker bark, as the increase in insulating properties provided by the swollen outer layer will protect the inner bark layers from swelling.

Pre- and post-treatment photographs show the swelling response of mature Douglas-fir to heating in a 200 °C environment for 10 min (Fig. 2). The rhytidome or outer bark is composed of pockets of dark material (dead secondary phloem) surrounded by a matrix of cork-like, lighter-colored tissue (periderm). Closer inspection suggests that the periderm swells, while the secondary phloem remains nearly constant in size. Figure 3 presents data from a small set of experiments conducted on bark samples that had been divided into periderm and phloem tissue. Efforts were made to ensure that each sample contained only periderm or phloem. Heating of the two different tissue components was done at 250 °C, and swelling measurements were collected at regular intervals. The data represent the average fractional change calculated from 10 samples, and the error bars denote the standard error associated with each sample set. The data suggest that swelling occurs primarily in the periderm. Measurements of change in dimension in the radial, axial, and tangential directions (relative to the stem axis) were collected. These data indicate that swelling occurs only in the radial direction.

Laboratory experiments that focused on the relationship between time and temperature indicated that swelling is dependent on both the magnitude and duration of heating (Fig. 4). Maximum swelling corresponded with maximum temperature. Swelling is relatively modest at 100 °C, with the most significant swelling occurring at temperatures above 100 °C. When the samples are placed in environments at temperatures greater than 125 °C, the swelling was largely complete

within 20 min. The samples displayed a decrease in dimension after a maximum was reached. However, even for heating durations as long as 36 h, the final swelling always exceeded 50% of the original size, even after shrinkage. The data indicate that swelling is greatest for temperatures well above the vaporization point of water, implying that swelling in Douglas-fir is related to the release of bound moisture and (or) volatile material from periderm cells.

Ponderosa pine

Ponderosa pine samples were collected from trees with diameters ranging from 4.9 to 13.1 cm and the corresponding bark thickness ranging from 1.9 to 11 mm. Figure 5 shows the measured swelling response. There are perhaps insufficient data for a meaningful regression, but the LOESS fit and associated confidence intervals are included to indicate trends and statistical significance. The data reveal that at least over the small sample set studied here, ponderosa pine does not exhibit significant swelling. Rather, a slight decrease in bark thickness is observed with heating, although the decrease may vanish as the stem diameter increases (i.e., larger original bark thickness). Because of the lack of any observed swelling response, further measurements over a broader range of diameters were not conducted. The heated and charred ponderosa pine bark samples were found to be particularly fragile. Once charred, the layers on the plates were observed to fall off, reducing the post-heating diameter. Hence, the effect is an apparent negative swelling (shrinkage). However, when a magnified image was monitored during the heating process, it was observed that, as the bark was heated, it initially expanded (5%–10%), followed by a slower, long-term shrinkage with the final bark thickness dimension being lower than the initial thickness. It is speculated that this shrinking is linked to drying during the heating process and the loss of small flakes of bark from the outer surface. At higher temperatures, a loss of bark also occurs because of ignition and sustained burning of the bark surface.

The apparent shrinkage of ponderosa pine bark exposed to a heating environment is at odds with the generally accepted understanding that ponderosa pine exhibits higher survivability in ground and surface fires than many other species (Agee 1998). It should be underlined that the bark of mature ponderosa pine and some other conifer species is rather thick, providing good insulation from thermal injury to the cambium despite the slight shrinkage. Further, the loss of the outermost layers of ponderosa pine bark during heating provides a sort of ablative protection to heating, constituting yet another mechanism for higher thermal tolerance. Finally, recent thermally induced tissue necrosis research has shown that of the four species included in this study, ponderosa pine cambial cells exhibit the highest resistance to thermal injury for temperatures above 45–50 °C (Dickinson et al. 2004). Thus, it is concluded that bark thickness represents only one mechanism protecting tree stems from thermal injury during wildland fires.

Red maple

A limited set of swelling data were collected for red maple, with diameters ranging from 4.9 to 12.5 cm and corresponding bark thickness from 1.5 to 3 mm. Measurements of fractional swelling of red maple bark reveal an approximately

Fig. 2. Photographs depicting the thickness of a cross-sectional sample of mature Douglas-fir (*Pseudotsuga menziesii*) bark prior to heating (photograph A) and after heating (photograph B). The scale shown in the photographs is in millimetres.
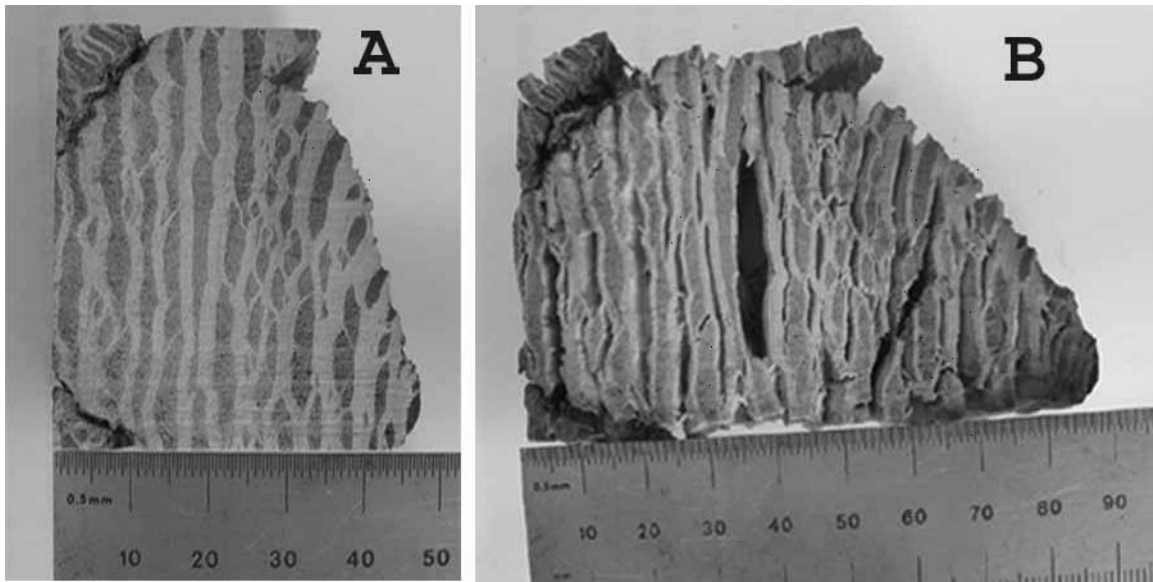

Fig. 3. The average change in dimension within the periderm and the dead secondary phloem of Douglas-fir (*Pseudotsuga menziesii*).
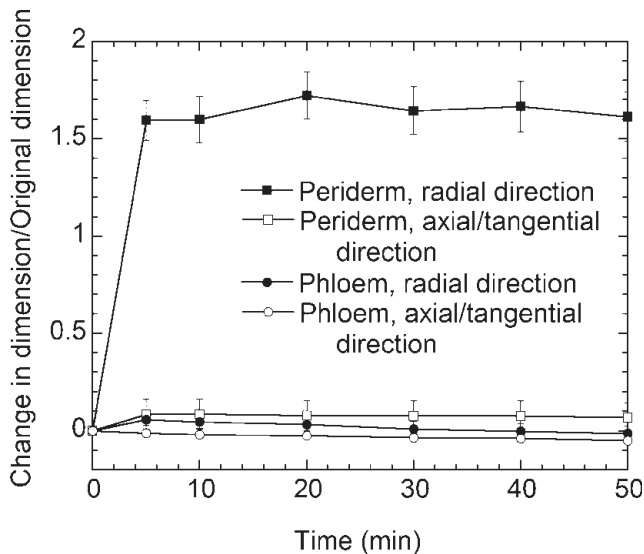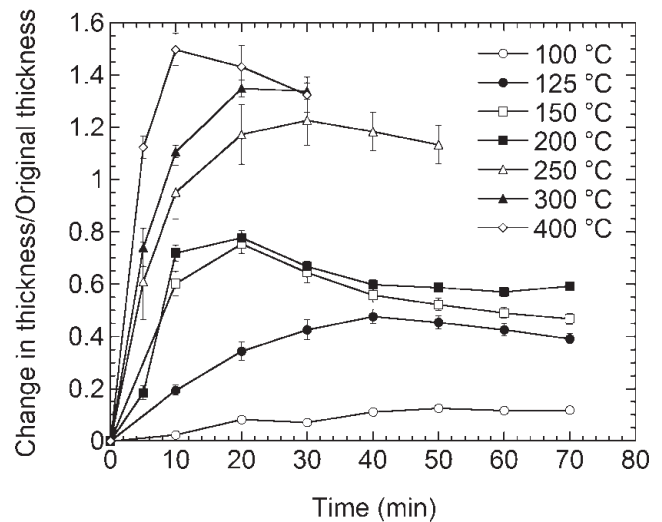

Fig. 4. Average fractional change in radial direction thickness as a function of time and heating temperature for Douglas-fir (*Pseudotsuga menziesii*) bark samples.

symmetric distribution around zero (Fig. 6). Although there are a limited number of data points, the results of the LOESS regression and associated confidence intervals suggest that swelling was not statistically significant for the red maple samples included in this study. Consequently, no further measurements were made.

Chestnut oak

Testing was conducted on samples with a range of diameters (6.8–26.1 cm with corresponding bark thickness ranging from 2 to 30 mm). The data indicate a 6%–8% average peak increase in overall bark thickness with a gradual decline in peak swelling as bark thickness exceeds 12 mm (Fig. 7). Change in radial diameter measurements were collected at 10-min intervals on freshly cut chestnut oak samples, and as shown in Fig. 8, the data indicate that swelling occurs only

at temperatures exceeding 200 °C. Each data point in the figure represents the average fractional change calculated from 10 samples, and the error bars denote the standard error associated with each sample set. For these elevated temperatures, the bark swells initially, reaches a maximum, and then steadily decreases in thickness. For temperatures at or below 200 °C, the bark exhibits a steady, long-term shrinkage.

Swelling is observed only for data corresponding with temperatures higher than 200 °C, implying that, as indicated by the Douglas-fir data (Fig. 4), swelling is not a free-moisture desiccation phenomenon, but rather, the result of driving bound moisture and (or) volatile material from the bark.

The structure of chestnut oak bark is significantly different from the bark of Douglas-fir. The rhytidome or outer bark seems to be composed primarily of the light colored periderm, while the inner bark is primarily phloem. The matrix

Fig. 5. In situ swelling response (change in bark thickness / original thickness) in ponderosa pine (*Pinus ponderosa*).
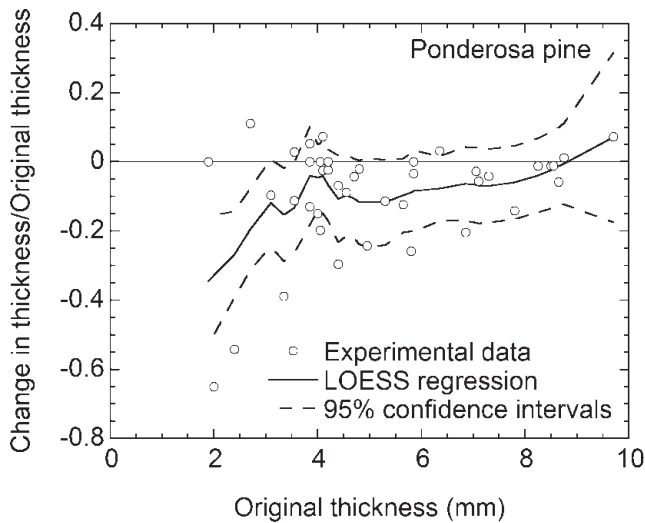

Fig. 6. Swelling response in red maple (*Acer rubrum*). The swelling data are normalized by the original bark thickness.
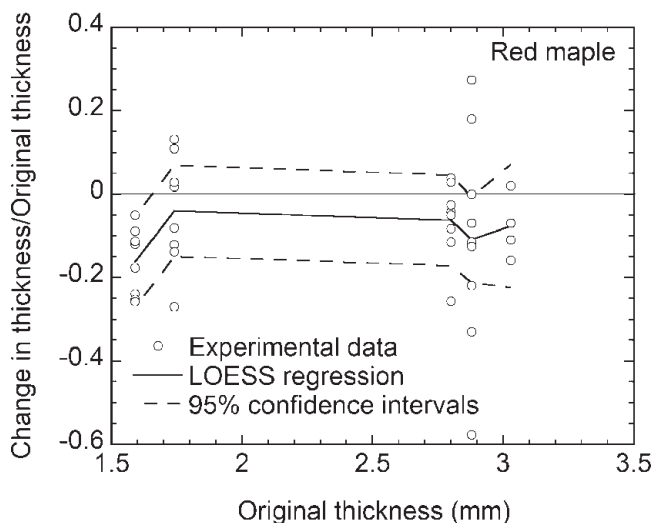

Fig. 7. In situ change in chestnut oak (*Quercus prinus*) bark as a function of initial bark thickness. The swelling data are normalized by the original bark thickness.
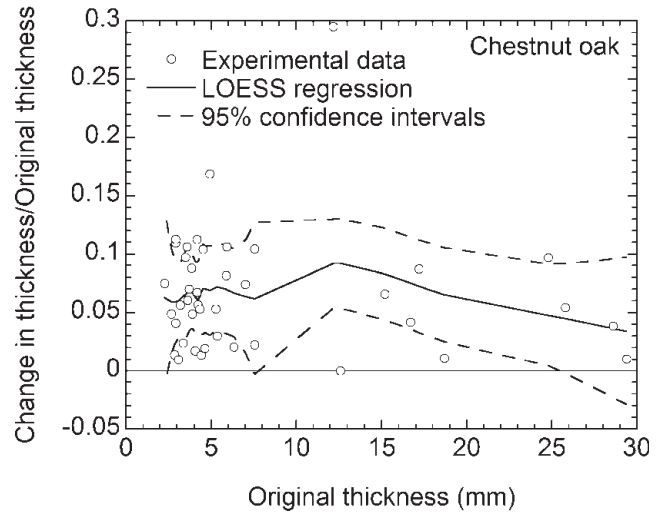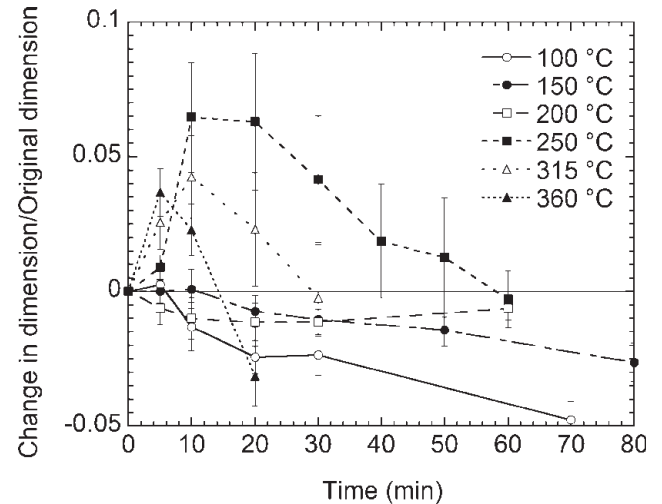

Fig. 8. Average fractional change in radial direction thickness as a function of time and heating temperature for chestnut oak (*Quercus prinus*) bark samples.

of periderm surrounding pockets of phloem like that observed in Douglas-fir does not exist. Figure 9 compares swelling of the outer bark layers (primarily periderm) and inner bark (primarily phloem) of chestnut oak exposed to a heating environment at a constant temperature of 250 °C. The data clearly indicate that the majority of the swelling in chestnut oak occurs in the outer layer. However, while swelling is manifest, the magnitude is low (i.e., nominally 5%).

Based on the data collected and presented in the foregoing sections, it is clearly established that thermally induced swelling occurs in Douglas-fir and, to a lesser degree, chestnut oak. The data indicate that the bulk of the swelling occurs at temperatures well above the vaporization temperature of water, suggesting that swelling is not a free-moisture desiccation phenomenon for these two species (Figs. 4 and 8), experiments were performed to confirm the independence of swelling on initial moisture. Data were collected from both freshly cut and oven-dried stem samples, as described previously, and are presented in Fig. 10. The data reveal no significant

differences between oven-dried and freshly cut samples for either species, corroborating that free moisture does not play a significant role in bark swelling. The lack of a clear difference in the magnitude of swelling between the dried and fresh samples suggests that if vaporization of water is one of the factors driving the swelling, it is due to water that is more tightly held in the cell than that driven off at typical drying oven temperatures (<100 °C) (Haygreen and Bowyer 1989).

Haygreen and Bowyer (1989) report that the lignin content of bark is significantly higher than that of wood and that lignin is considered the "glue" that binds the cells together. It is also suggested that lignin becomes soft and pliable as it is heated. Others have shown that pyrolysis of bark begins at 150 °C and peaks at 350 °C, after which it declines and is largely complete by 500 °C (Susott 1982). The data presented in Figs. 4 and 8 indicate that swelling starts at a temperature exceeding 125 °C for Douglas-fir and 250 °C for chestnut oak, and that it continues to temperatures above

Fig. 9. The average change in thickness due to heating for the inner and outer bark of chestnut oak (*Quercus prinus*).
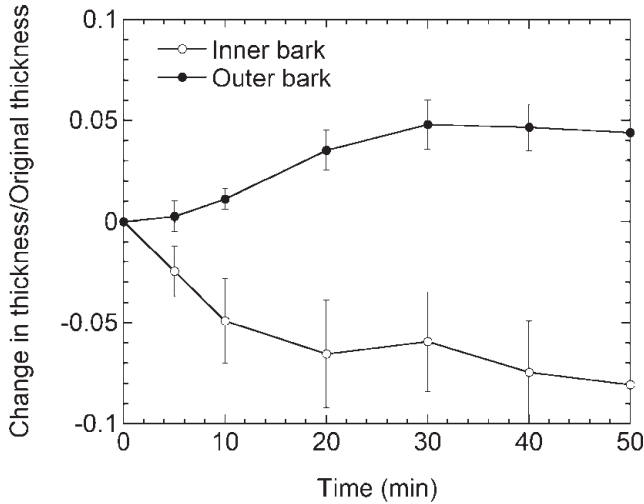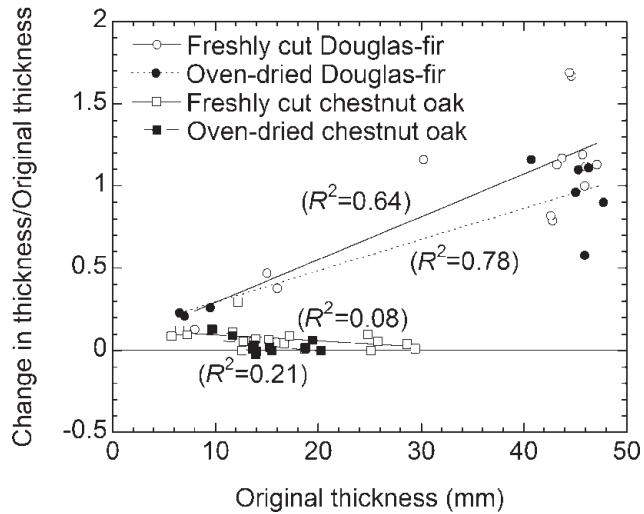

Fig. 10. The effect of moisture content on swelling in Douglas-fir (*Pseudotsuga menziesii*) and chestnut oak (*Quercus prinus*).

Fig. 11. Empirical correlation of peak change in bark radial dimension as a function of bark temperature for Douglas-fir (*Pseudotsuga menziesii*) bark samples.
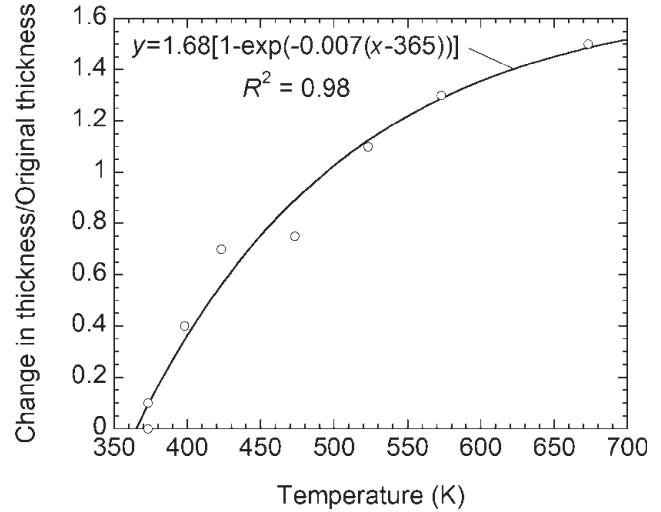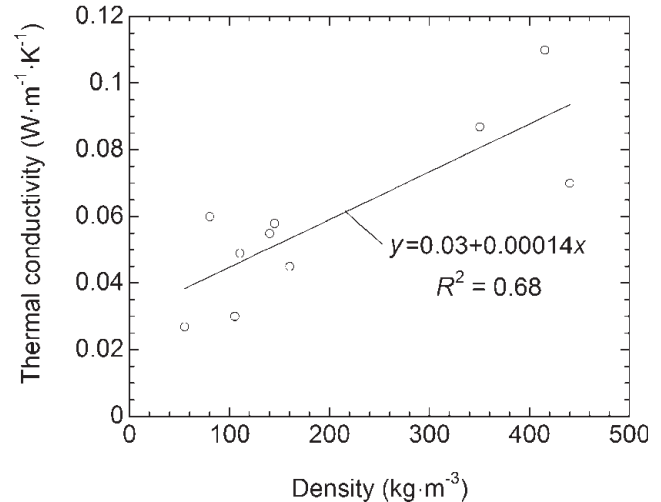

Fig. 12. Published values of thermal conductivity versus density for a range of woody materials at 27 °C (Incorpera and DeWitt 2002).

400 °C, approximately the same range identified by Susott over which pyrolysis occurs. The measurements included in Figs. 4, 8, and 10 do not definitively identify the mechanism by which the swelling occurs. The data suggest that swelling may be linked to thermally driven processes other than the desiccation of free moisture, such as the release of tightly bound moisture and (or) the pyrolysis of the outer bark. The process is likely complex, as the pyrolysis of wood and bark involves many phases including heating, drying, mass transfer, solid fuel pyrolysis to volatiles and char, gas phase oxidation, and char oxidation (Tillman et al. 1981).

A simple empirical correlation of the measured data has been developed between peak swelling in the radial dimension for Douglas-fir bark and bark (oven) temperature (Fig. 11). The correlation indicates that temperature (as opposed to moisture content, heating rate, etc.) accounts for most of the variation in bark swelling. The regression suggests that the onset of swelling for Douglas-fir occurs at a temperature

slightly above 100 °C (373 K), and that the swelling process is largely complete at approximately 350–400 °C (623–673 K).

Dry bark density can be estimated by weighing oven-dried samples and then dividing that mass by a volume determined from the water displaced in a graduated beaker into which the sample is placed. This method assumes negligible water absorption by the samples. For this study, samples were immersed in water for less than 30 s to minimize water absorption. Visual observations suggested that the bark samples were slightly hydrophobic and that water absorption was not significant. Such measurements yielded an effective bulk density for mature Douglas-fir bark of 420 kg·m^{-3} which, according to Martin (1963a, 1963b), corresponds with a thermal conductivity of 0.07 W·m^{-1}·K^{-1}. Laboratory measurements on samples of Douglas-fir bark that had been heated in an oven for 30 min at 250 and 400 °C yielded effective densities of 183 and 110 kg·m^{-3}, respectively. If one focuses just on woody materials as plotted in Fig. 12, a relatively weak de-

pendence of thermal conductivity on density (linear relation with an approximate slope of 1/7000) is observed from limited published data (Incropera and DeWitt 2002). Accurate experimental measurements of thermal conductivity are difficult to achieve and, consequently, were not attempted in this study. By using the data presented in Figs. 11 and 12, it is possible to estimate the magnitude of swelling in Douglas-fir bark and the corresponding decrease in thermal conductivity.

The bark swelling observed in the data presented in the foregoing affects the density and therefore, the thermal diffusivity. The thermal diffusivity is a measure of a material's ability to transport thermal energy by conduction relative to its ability to store thermal energy and is the ratio of the thermal conductivity k to the product of density ρ and specific heat C (Incropera and DeWitt 2002). An estimate of the swelling-induced decrease in k relative to that of ρC reveals that the thermal diffusivity may change by as much as a factor of two or three, due principally to the decrease in k. For thin cylindrical shells whose shell thickness is small compared with the radius, the resistance to energy transfer R can be approximated as the shell thickness t divided by the material's thermal conductivity k ($R = t/k$) (Incropera and DeWitt 2002). The effect of bark swelling on the temporal response of stems exposed to fire conditions was previously explored using a numerical model developed to predict unsteady thermal transport in stems. The model accounts for temperature- and moisture-dependent properties (k, ρ, and C), as well as desiccation and pyrolysis. Thus, the model includes the impact of bark swelling, and property dependence on temperature and moisture on the thermal diffusivity. It was shown that an increase in local bark thermal resistance of 175% resulted from a modeled swelling-induced increase in bark thickness of 20%–30% above the initial value (Jones 2003; Jones et al. 2004). This effect would be greater locally near the exterior of the stem surface that exhibited greatest swelling. Jones assumed that the effect of swelling was to increase the bulk volume, thereby decreasing the density and thermal conductivity. The bark swelling was shown to have a substantial impact on predicted cambial temperatures. For a typical mature Douglas-fir stem burn scenario that included desiccation, bark swelling, and pyrolysis, the model predicted a peak cambial temperature of 43 °C. If bark swelling was neglected, the cambial temperature increased by 8 °C. Such a temperature difference significantly influences the resultant thermal injury to the cambium (Dickinson and Johnson 2001; Dickinson et al. 2004). Further, it was shown that while bark swelling did not have the largest effect on cambial temperature predictions, its influence was among the most significant (Jones 2003; Jones et al. 2004).

While the samples studied do not represent broad geographic, seasonal, or physiologic ranges, the results suggest that thermally induced swelling may be a species-specific response to fire and that additional efforts should be directed at characterizing that response through a statistically complete sample set. The results of this study combined with the conclusions reached by Jones et al. (2004) suggest that accurate understanding and models of stem heating and subsequent mortality should consider thermally induced bark swelling as a species-specific response to fire. The results imply that species-specific physiology and adaptation to fire is due to a variety of factors including bark thickness, thermally induced swelling, and possibly tissue or cell level response.

Conclusions

The data presented herein suggest the existence of thermally induced bark swelling, a previously undocumented species- and temperature-dependent plant response to fire. Measurements were made on a limited sample set collected from four species. For the species that exhibited thermally induced swelling, the response occurred within minutes of exposure to a heat source, leading to a decrease in bulk thermal conductivity of the bark. Results indicated that swelling was greatest in Douglas-fir. Swelling in chestnut oak was small, but statistically significant. Ponderosa pine and red maple bark exhibited, in general, a slight negative swelling (i.e., shrinkage) with heating, although neither was appreciable. The onset of swelling in the Douglas-fir samples was observed at a temperature exceeding 100 °C, with peak swelling occurring at 300 °C. As the bark matures, the plate–fissure structure characteristic of Douglas-fir develops, and only then is the development of thermally induced bark swelling clearly demonstrated. Swelling occurs throughout the rhytidome but seems to be confined primarily to the periderm, occurs only in the radial direction (relative to the plant stem), and can reach magnitudes greater than 150% locally. Nominal increases in Douglas-fir total bark thickness were as high 30%, and were found to be largest for stems with a total bark thickness of approximately 20 mm. As the thickness increased, the relative change in total thickness decreased. Swelling in chestnut oak initiated at approximately 225 °C and peaked at 250 °C with decreased swelling at higher temperatures. The moisture content of the bark did not appreciably affect the magnitude of swelling in the Douglas-fir and chestnut oak.

The limited measurements presented here suggest that bark swelling may be a significant response to fire and that it can result in increased protection of the stem cambium. There are numerous practical and physical limitations involved in whole live tree sampling. Because of these sampling constraints, these data do not represent the full range of variability present within and between species. It is recognized that fire resistance is not only dependent on bark thickness but also varies across geographical location and season (Brown and DeByle 1987). Additional work is needed to further quantify the response of these species across their distribution range and during different phenomenological stages.

Bark swelling appears to represent a mechanism by which the vascular cambium is further insulated against thermal damage due to fire-induced heating. Characterization of bark swelling is important to make accurate predictions of stem heating and subsequent thermally induced tissue damage.

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