Bark Thermal Properties of Selected Central Hardwood Species

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Abstract: Some physical, thermal, and chemical properties of bark of eleven tree species native to the central hardwood region were measured to determine their potential to protect the vascular cambium from damage by fire. The relationship between dbh and bark thickness for each of sixteen species was determined. For purposes of monitoring seasonal trends, two species (Quercus macrocarpa Michx. and Acer saccharinum L.) were sampled periodically during one growing season. Heat transfer through bark tissue of eleven species was monitored during simulated fires conducted in the field. Bark samples were analyzed for moisture content, specific gravity, dry weight, and time until ignition, and subjected to standard test methods for determination of volatile matter content. Overall, heat flux and maximal cambial temperatures during simulated fires were reduced as bark thickness increased. Thick-barked species had lower maximal temperatures, longer times to reach peak temperatures, slower rates of heat loss, and shorter time until surface ignition. Populus deltoides Marsh. was the most fire resistant among species tested, while Acer saccharinum was the least. Specific gravity was positively correlated with thermal conductivity and likely influenced the rate at which cambial temperatures rose as well as the time required for surface ignition. Moisture content was lower in thin-barked species with higher specific gravities.

INTRODUCTION

A fundamental assumption of fire ecology is that fire in the natural landscape is neither inherently destructive nor constructive; it merely brings about change. Historically fire has been considered by foresters to be undesirable in the central hardwood region of North America due to its damaging effect on hardwoods with high veneer and sawlog values. However, prescribed burns are becoming increasingly commonplace as resource managers learn the values of periodic fires to supplement natural processes (Wade and Lunsford 1989). The replacement of early-to-mid-successional *Quercus* species as the predominant constituents of eastern hardwood forests by the more shade-tolerance, mid-to-late-successional *Acer* species may be the result of a reduced fire frequency policy (Wuenscher and Valiunas 1967, Grimm 1983, Nigh et al. 1985, Abrams 1986). The transition of *Quercus* species to later successional species will likely continue without control of competing species (Abrams and Scott 1989). Reduced survival and reproduction of mesic *Acer* species to fire and the relative fire resistance of many central North American *Quercus* species (Reich et al. 1990) suggest that the current transitional trend may be reversed through use of prescribed burns
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Alternate methods of vegetation management such as herbicide application and mechanical control are high in cost relative to prescribed burning. However, without a thorough understanding of the effects of fire on hardwood species, prescribed burns cannot be used to achieve a predictable outcome (Green and Shilling 1987).

Little is known about the fire tolerance of central hardwoods. Our study objectives were to obtain empirical information on physical and thermal properties of bark of several native tree species, and

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to establish relationships among properties indicative of fire tolerance and critical heat levels of vascular cambial tissue of trees exposed to fire. The research concentrated on two questions:

1) Do thermal characteristics of bark differ among species?
2) Do physical and chemical properties of bark relate to a species' fire tolerance?

MATERIALS AND METHODS

Study sites

The trees studied were located in the Illini Forest Plantations (40°04'N Lat., 88°12'W Long.), Brownfield Woods (40°09'N Lat., 88°10'W Long.), and Trelease Woods (40°09'N Lat., 88°09'W Long.), all located near Urbana, Illinois, and Robert Allerton Park (39°59'N Lat., 88°39'W Long.), near Monticello, Illinois. In addition, trees located in Forest Glen County Preserve (41°59'N Lat., 87°45'W Long.), near Georgetown, Illinois, and Kennekuk Cove County Park (40°10'N Lat., 87°45'W Long.), near Danville, Illinois, were studied. The Illini Forest Plantations contain plantings of hardwood and softwood species approximately 40 years old *Prunus serotina* Ehrh., is a volunteer species in the Illini Forest Plantations and younger than the other trees measured. Plant communities at the other sites were representative of common mesophytic forest types of the Midwest, and are dominated by *Acer saccharum* Marsh. replacing for dominant *Quercus* species.

DBH and Bark Thickness Measurements

As bark thickness is a commonly used indicator of fire tolerance (Starker 1934, Hare 1961, Spalt and Reifsnyder 1962, Hare 1965, Vines 1968, Uhl and Kauffman 1990), measurements of dbh (diameter at breast height of 1.4 m) and bark thickness were made of sixteen upland and lowland species at all the locations listed above to determine the relationship of the two values across several age, site, and size categories. The species examined were *Acer saccharinum* L. (silver maple), *Acer saccharum* Marsh. (sugar maple), *Fraxinus americana* L. (white ash), *Juglans nigra* L. (black walnut), *Liquidambar styraciflua* L. (sweetgum), *Liriodendron tulipifera* L. (tulip-poplar), *Platanus occidentalis* L. (sycamore), *Populus deltoides* Marsh. (eastern cottonwood), *Prunus serotina* Ehrh. (black cherry), *Quercus alba* L. (white oak), *Quercus imbricaria* Michx. (shingle oak), *Quercus macrocarpa* Michx. (bur oak), *Quercus muehlenbergii* Engelm. (chinkapin oak), *Quercus rubra* L. (red oak), *Tilia americana* L. (American basswood), and *Pinus strobus* L. (Eastern white pine). Bark thickness on each of these trees was made with a standard bark gauge and recorded to the nearest mm. Measurements were made 1.3 m above ground level on the north and south sides of each tree. Diameters were determined to the nearest mm.

Determination of Bark Physical Properties

Bark samples were collected from three randomly-selected trees of each of the following eleven study species grown in single-species plots of approximately 0.4 ha each at the Illini Forest Plantations, where destructive sampling was permissible: *A. saccharinum*, *F. americana*, *J. nigra*, *L. styraciflua*, *L. tulipifera*, *P. occidentalis*, *P. deltoides*, *P. serotina*, *Q. macrocarpa*, *T. americana*, and *P. strobus*. In this study bark is defined as all tissues located outside the vascular cambium. Samples were taken from the same plots of the eleven species of similar-aged trees that were subjected to fire treatments. Trees with apparent mechanical injury or disease were excluded from sampling. Dbh and bark thickness were measured and recorded from each sample tree. Bark samples were 5 x 5 cm in size and removed from the north and south sides of each of three trees per species. Only trees in the plot interiors were sampled. Samples were taken at 1.5 m height and were removed by cutting through the bark with a chisel. Preliminary measurements of the trees under study showed bark thickness to be the same at that height as within 50 cm of the soil, where ground fires would likely impact trees. Samples were taken from all species on July 22, 1992, while samples of two species, *Q. macrocarpa* and *A. saccharinum*, were also obtained from different trees in the same plots on April 21 and October 21, 1992 for seasonal comparisons. Samples were sealed immediately in airtight plastic bags and stored frozen for laboratory analysis.

Moisture content, specific gravity, percentage volatile matter, and time till ignition were ascertained in the laboratory from the bark samples. Six samples per species (two per tree) were tested. Samples were placed in a drying oven for 96 hours at 64°C to achieve a uniform moisture level. Comparisons of field and oven-dry weights were then made to determine moisture content on a dry mass basis (% moisture = [field mass - oven-dry mass] / [oven-dry mass] X 100). Volume was measured by the mass displacement method and used to calculate bark specific gravity (g/cm3). Thermal conductivity (k) of bark of each species was calculated using the following formula: k = (4.684r + .076) x 10-4 cal/cm/sec°C (r is bark density, g/cm3) (Wenger 1984). After setting aside one quarter of each sample for ignition comparisons, remaining portions were ground to pass through a 20 mesh screen and dried for volatile matter analysis according to test methods described in the American Society for Testing and Materials designation D1762-84 (ASTM 1992). Crucibles containing one g of ground sample were each heated in a muffle furnace to 500°C. Percentage of volatile matter in each sample was determined from weight loss after heating. Comparisons of time until ignition of bark chunks were made at 300°C and 600°C. Chunks of consistent weight (1.35 g) were oven-dried. The door on the muffle furnace used in the ignition tests was left partially open to allow sufficient oxygen to reach the samples so that combustion could occur. An additional thermocouple probe was positioned next to the sample in the furnace to measure temperature levels at time of ignition. For this study, ignition was the instant at which glowing was observed on the surface of each bark sample.

Fire Simulations

Heat transfer through bark tissues was measured in the field using a modified wick-fire technique (Hare 1965, Uhl and Kauffman 1990). This method has been shown to create a heat pulse similar to that found in natural fires. A 1.5-cm diameter cotton rope soaked in kerosene provided the fuel for the fire simulation. The rope, in lengths one-half the diameter of each tree, was centered and attached 10 cm below the tip of a MgO-filled Inconel 600 sheath thermocouple probe (Inconel Corporation, Forestry Suppliers, Inc., Jackson, MS) inserted between the bark and the cambium. Because the trees subjected to fire simulations were of different diameters, these varying lengths of rope allowed for uniformity of heat levels per unit surface area. The flexible high temperature probe was positioned for the purpose of measuring cambial temperatures during the fire by inserting the tip 10 cm downward under the bark through the gap left by removal of a bark sample. A second thermocouple was positioned on the bark surface directly opposite the inserted probe. All burns were conducted on the north side of each tree to eliminate possible temperature influence by solar heating. Immediately before each burn, ambient air and cambial temperatures were recorded. Temperatures were recorded every ten seconds after ignition of the fuel source, until external bark temperatures stabilized at or near ambient levels.

Statistical Analyses

Linear regression analysis was used to compare dbh and bark thickness variables. The linear method provided better correlation coefficient values than did nonlinear methods. One-way ANOVA for the species and Duncan's Multiple Range test was applied to bark variables. A Pearson correlation matrix was used to determine correlations among values of bark properties. Methods used are described in **SAS User's Guide: Basics** and **SAS User's Guide: Statistics**, version 5 editions (SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

DBH and Bark Thickness Measurements

P. deltoides and *Q. macrocarpa* had significantly higher dbh values and bark thickness than the other fourteen species. Regression analyses from the data indicate a strong relationship of bark thickness and dbh for most species measured (Figures 1-16). The rate of increase between bark

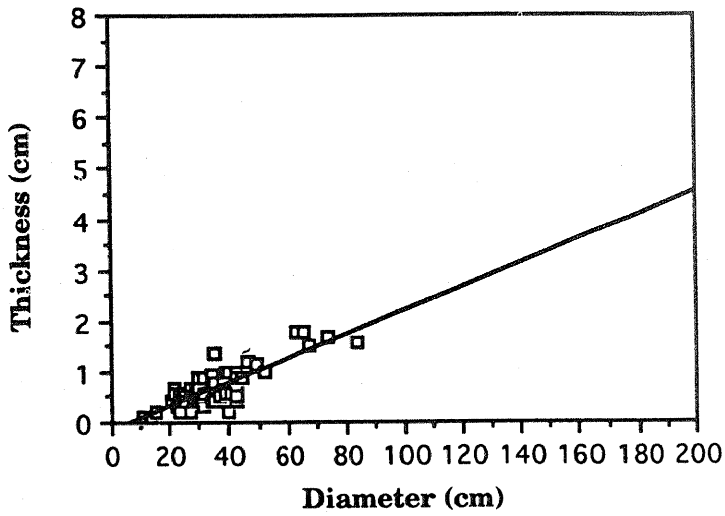

Figure 1.—Bark thickness vs. dbh for *Acer saccharinum*.

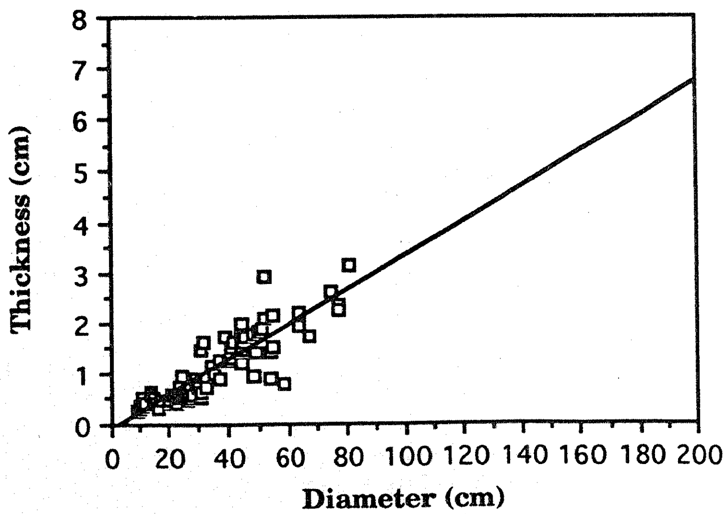

Figure 2.—Bark thickness vs. dbh for *Acer saccharum*.

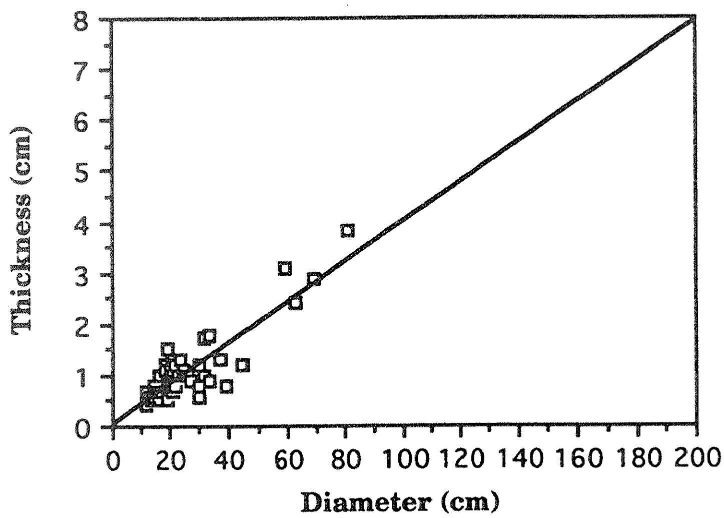

Figure 3.—Bark thickness vs. dbh for *Fraxinus americana.*

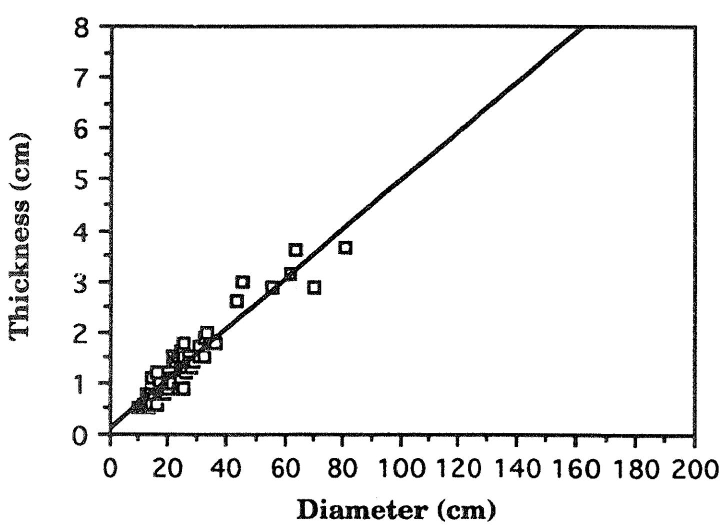

Figure 4.—Bark thickness vs. dbh for *Juglans nigra.*

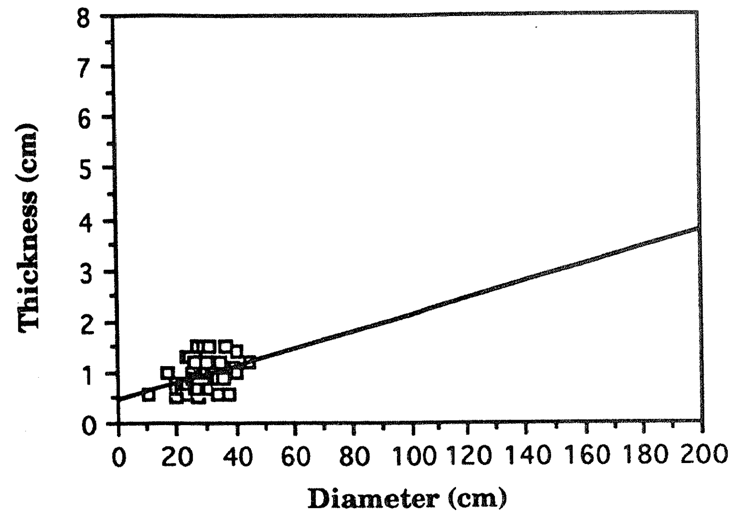

Figure 5.—Bark thickness vs. dbh for *Liquidambar styraciflua.*

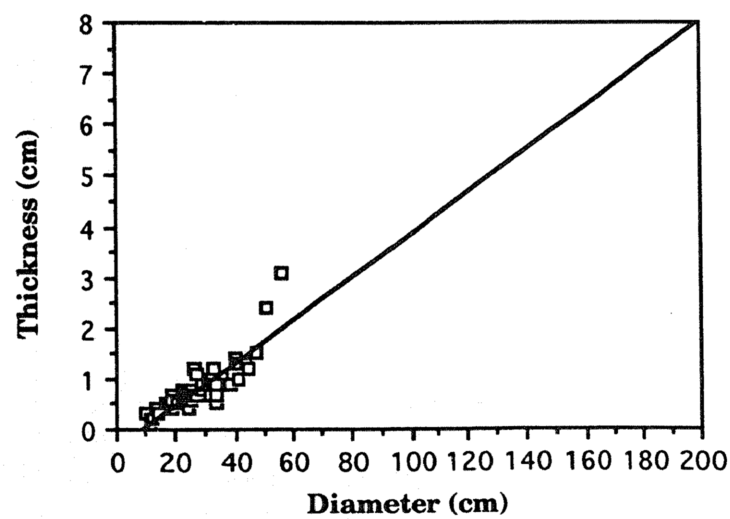

Figure 6.—Bark thickness vs, dbh for *Liriodendron tulipifera.*

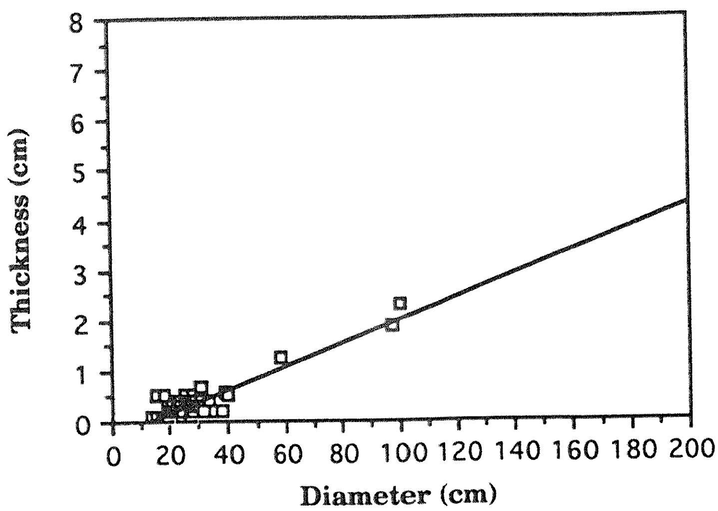

Figure 7.—Bark thickness vs. dbh for *Platanus occidentalis*.

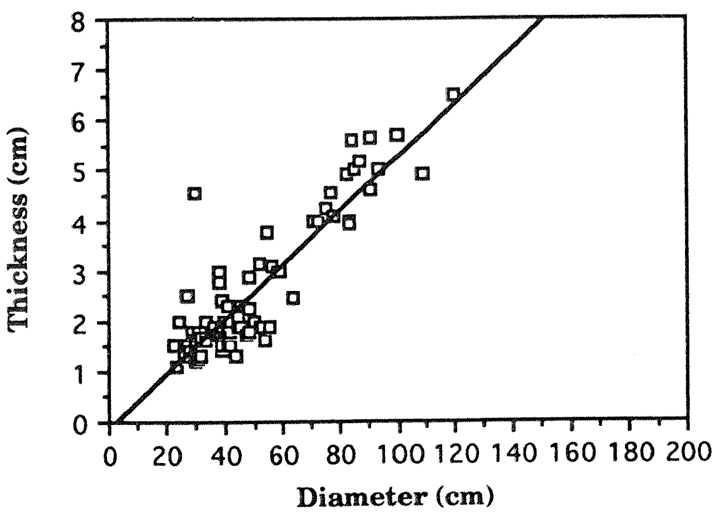

Figure 8.—Bark thickness vs. dbh for *Populus deltoides*.

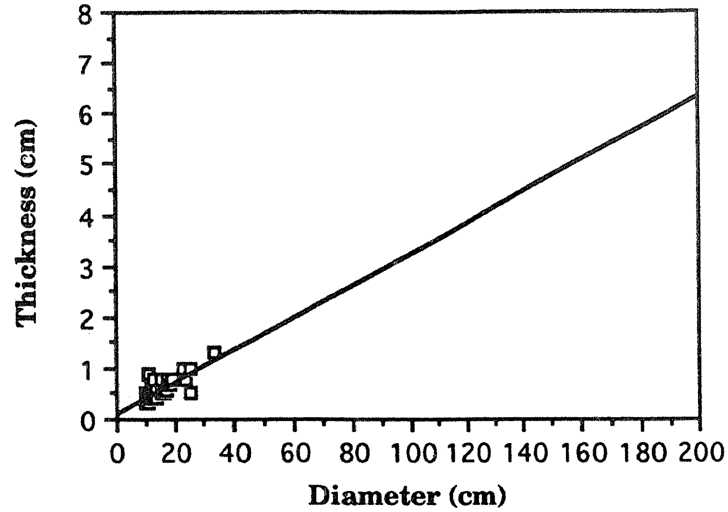

Figure 9.—Bark thickness vs. dbh for *Prunus serotina*.

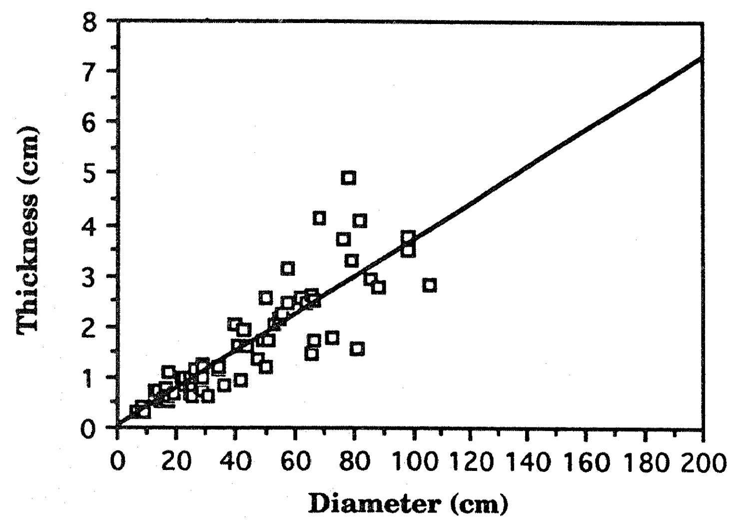

Figure 10.—Bark thickness vs. dbh for *Quercus alba*.

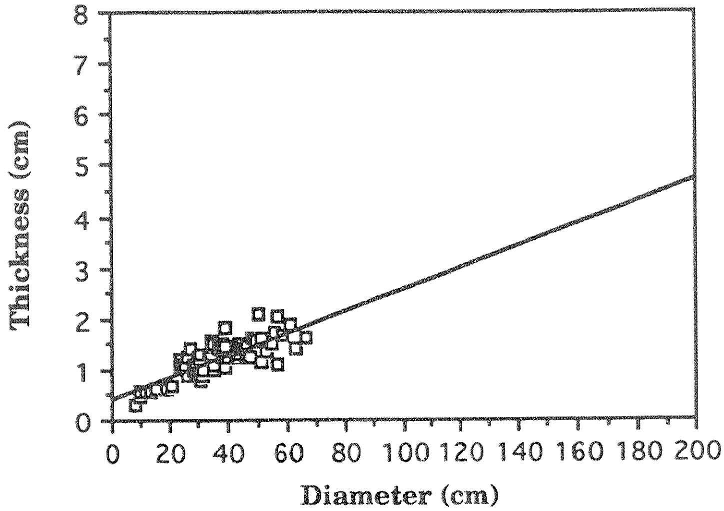

Figure 11.—Bark thickness vs. dbh for *Quercus imbricaria*.

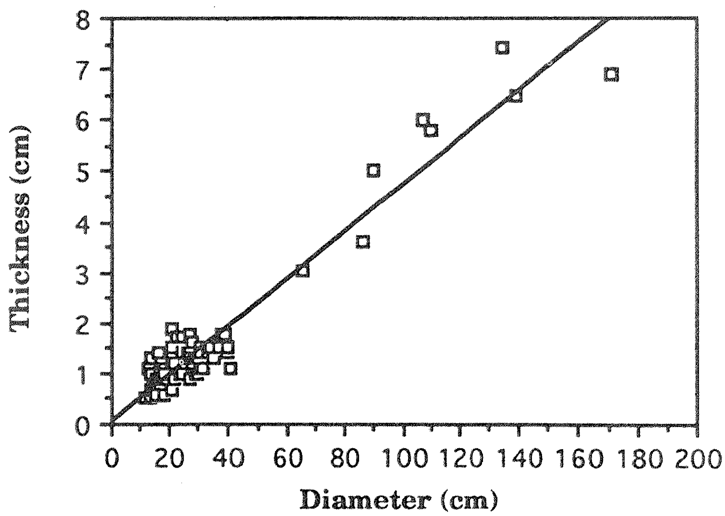

Figure 12.—Bark thickness vs. dbh for *Quercus macrocarpa*.

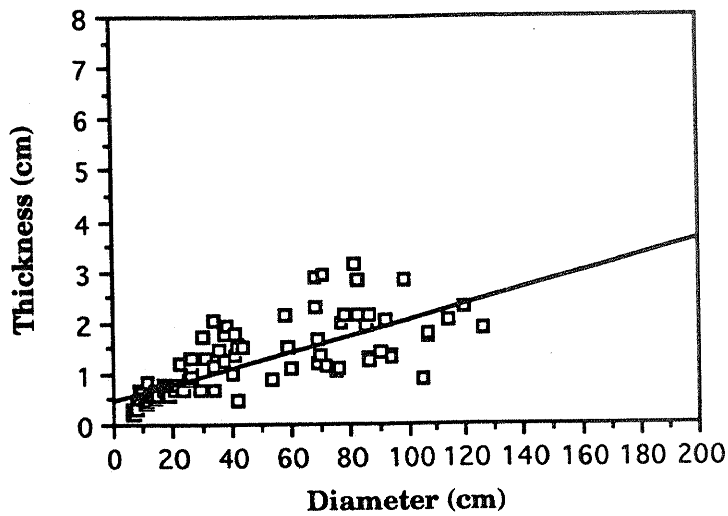

Figure 13.—Bark thickness vs. dbh for *Quercus muehlenbergii.*

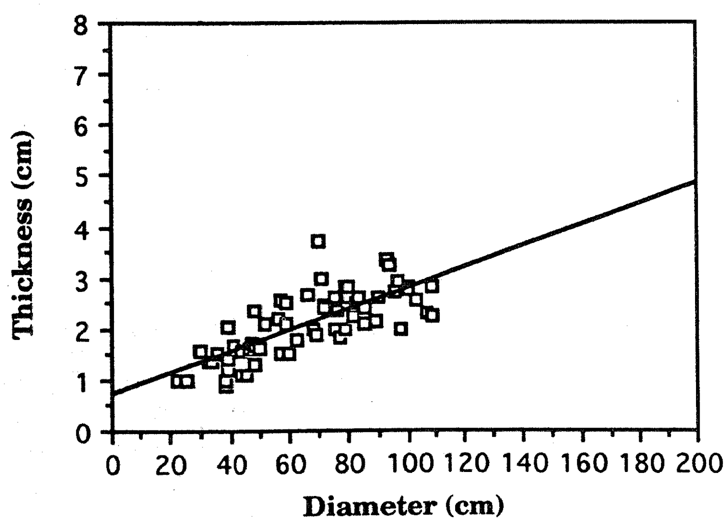

Figure 14.—Bark thickness vs. dbh for *Quercus rubra.*

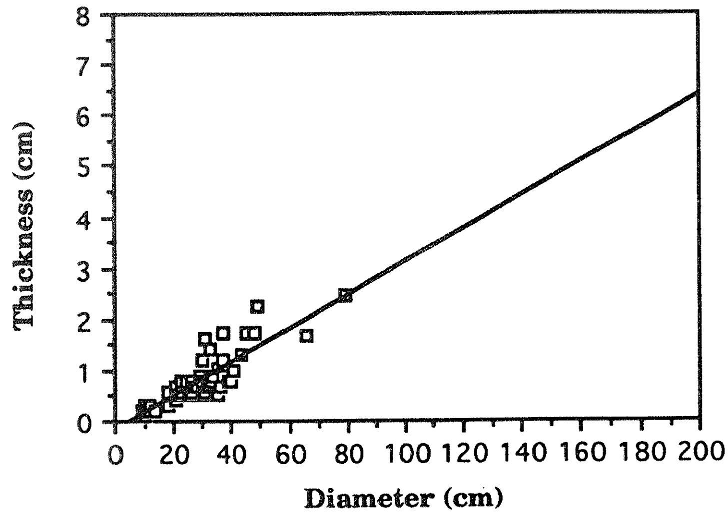

Figure 15.—Bark thickness vs. dbh for *Tilia americana*.

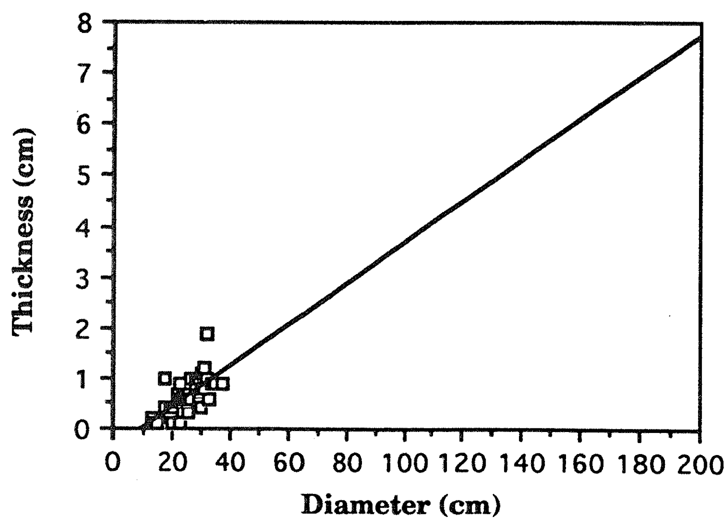

Figure 16.—Bark thickness vs. dbh for *Pinus strobus*.

Table 1.—Linear regression equations and correlation coefficients of bark thickness as a function of dbh for sixteen native tree species.

Tree species	Regression equation (y = mx + b)	r^2	No. of trees measured
Acer saccharinum	y = 0.0237x - 0.1529	0.66	63
Acer saccharum	y = 0.0343x - 0.1290	0.76	74
Fraxinus americana	y = 0.0395x + 0.0680	0.78	54
Juglans nigra	y = 0.0487x + 0.0962	0.89	63
Liquidambar styraciflua	y = 0.0163x + 0.4780	0.14	50
Liriodendron tulipifera	y = 0.0419x - 0.3558	0.74	52
Platanus occidentalis	y = 0.0229x - 0.2982	0.84	53
Populus deltoides	y = 0.0540x - 0.1568	0.85	85
Prunus serotina	y = 0.0310x + 0.1295	0.57	53
Quercus alba	y = 0.0367x + 0.0277	0.76	71
Quercus imbricaria	y = 0.0215x + 0.4410	0.63	69
Quercus macrocarpa	y = 0.0466x + 0.0705	0.93	64
Quercus muehlenbergii	y = 0.0157x + 0.4954	0.56	100
Quercus rubra	y = 0.0206x + 0.7198	0.56	64
Tilia americana	y = .0326x - 0.1708	0.70	59
Pinus strobus	y = 0.0405x - 0.3682	0.59	52

thickness with increasing stem diameter was greatest for *Q. macrocarpa* and least for *L. styraciflua* (Table 1 and Figures 1-16). The ranking of oaks in order of the rate of increase of bark thickness with radial growth of stem is *Q. macrocarpa* > *Q. alba* > *Q. inbricaria* > *Q. rubra* > *Q. muehlenbergii*. *Q. imbricaria* and *Q. rubra* are members of the red oak group and have lower rankings than two drier species in the white oak group. However, these members of the red oak group typically have faster growth rates than the other oaks in this study. *Q. rubra* is more mesic, has shallower roots, and requires better site conditions than other central North American oaks (Burns and Honkala 1990). The slope for *Q. muehlenbergii* (Table 1 and Figure 13) was the lowest among the species under study due to prevalence of the nonparasitic smooth patch fungus (*Aleurodiscus oakesii*) found on the bark. Smooth patch disease reduces bark thickness primarily of members of the white oak family. All but the youngest individuals of *Q. muehlenbergii* were affected. Such common occurence of the disease did not appear to affect the general health of the trees. However, protection from fire would likely be decreased due to the reduction of bark thickness. Table 2 shows the maximum bark thickness values found for each of the sixteen species. The largest individual trees examined in this study were *Q. macrocarpa* (134 cm maximum dbh). Upland species had proportionately greater bark thickness in relation to dbh in comparison with bottomland species, with the exception of the predominantly riparian *P. deltoides*.

Fire Simulations

Bark tissue can protect the vascular cambium from damage by fire. Overall trends show greater cambium protection with an increase in bark thickness (Figure 17). Maximum mean temperature of the cambium during fire simulation in planted trees of similar age ranged from 107.5°C (225.5°F) in *A. saccharinum* with thin bark (7.2 mm) to 50.4°C (122.7°C) in *P. deltoides* with thick bark (26.2 mm). Figure 18 illustrates the difference between internal and external temperature

Table 2.—Maximum bark thicknesses and corresponding dbh found in a sampling of native central hardwood species. For any species a minimum of 50 and a maximum of 100 trees make up the population from which the maximum value was obtained. Maximum values are from trees at least 40 years old occuring in plantations and natural stands.

Tree species	Maximum bark thickness (cm)	Corresponding dbh (cm)	Maximum thickness/ maximum dbh %
Quercus macrocarpa	7.4	134.3	11.0
Populus deltoides	6.5	120.0	10.8
Quercus alba	4.2	68.2	12.3
Fraxinus americana	3.8	81.6	9.3
Quercus rubra	3.7	69.9	10.6
Juglans nigra	3.6	81.0	8.9
Quercus muehlenbergii	3.2	82.2	7.8
Acer saccharum	3.2	80.9	7.9
Liriodendron tulipifera	3.1	56.3	11.0
Tilia americana	2.4	79.7	6.0
Platanus occidentalis	2.3	100.3	4.6
Quercus imbricaria	2.1	50.2	8.4
Pinus strobus	1.9	31.6	12.0
Acer saccharinum	1.8	65.4	5.5
Liquidambar styraciflua	1.5	36.5	8.2
Prunus serotina	1.3	34.0	7.6

fluxes in the example of a small individual *Q. macrocarpa* tree during a simulated burn. Table 3 lists mean maximal cambial temperatures recorded during the simulated fires, as well as the time that the temperatures remained above 60°C. Exposure to at least 60°C for 60 seconds or longer generally causes death of vascular plant tissues (Wright and Bailey 1982). Because cambial temperatures in all individuals of six of the species subjected to burns remained above 60°C for greater than 70 seconds and for as long as 910 seconds, these six species would likely be killed or scarred by a fire of similar intensity to the artificial fire in this study (Table 3). Flame length during the fires reached a mean of 42 ± 2.8 cm, representing a surface fire of low intensity. An additional four species had only one or two individuals that sustained lethal temperatures. *P. deltoides* maintained maximal cambial temperatures below 60°C for all individuals. An increase in the number of individuals that sustained lethal temperatures corresponds with increases in maximum cambial temperatures and increases in mean time above 60°C.

During the burns, cambial temperatures tended to rise rapidly in thin-barked species, reaching maximum temperatures in six minutes or less. Tree species with thick bark had lower maximum cambial temperature, longer lag times until maximum temperatures were achieved, and slower rates of heat loss from the cambial region following temperature peaks.

Maximum external bark temperatures ranged widely among the species burned, regardless of the relative consistency of flame length found in the simulated fires (Table 3). This variability of temperatures suggests that external bark structure influences absorption of heat. Several species with smoother textured bark maintained lower peak temperatures than those with thicker, fissured

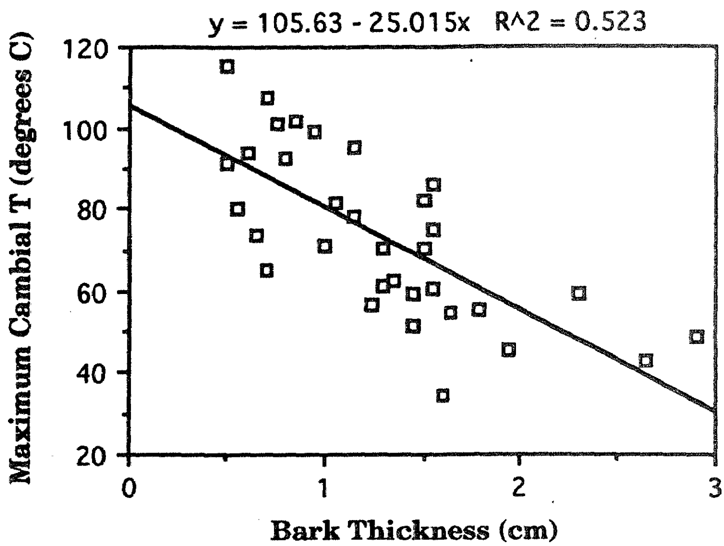

Figure 17.—The relationship between bark thickness and maximal cambial temperature for 33 individuals of 11 species during simulated fires.

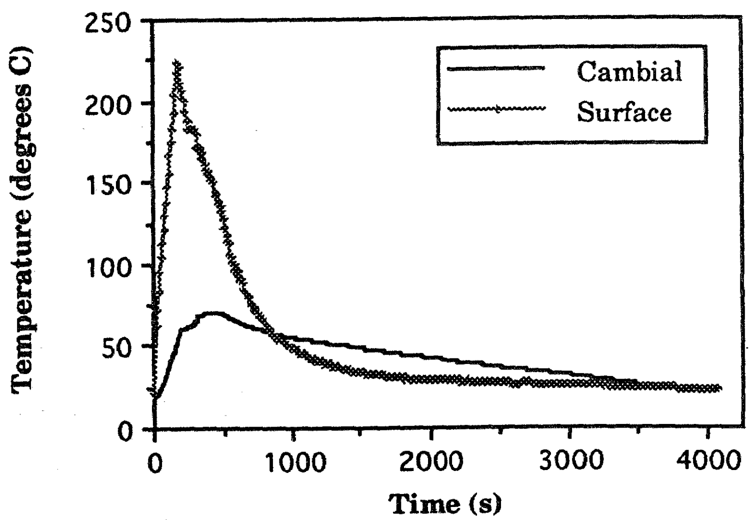

Figure 18.—Cambial and surface temperature fluxes for *Quercus macrocarpa* during a simulated fire.

Table 3.—Maximal cambial and bark surficial temperatures and duration of lethal cambial temperatures in relation to bark thickness of 40 year old trees subjected to simulated fire (n=3).

Tree species	Mean maximal cambial temperature (°C)	Mean cambial time above 60° (minutes)*	Mean bark thickness (cm)	Mean maximal external temp. (°C)
Populus deltoides	50.4	0	2.6	347.7
Pinus strobus	52.0	1.8 (1)	1.4	118.7
Quercus macrocarpa	57.1	3.1 (1)	1.5	267.1
Tilia americana	64.4	3.8 (1)	1.4	290.3
Juglans nigra	68.1	5.6 (2)	1.5	421.6
Prunus serotina	72.8	6.7 (3)	0.9	171.1
Liriodendron tulipifera	76.1	8.1 (3)	1.5	297.3
Fraxinus americana	78.4	7.8 (3)	1.2	321.1
Platanus occidentalis	81.8	9.0 (3)	0.6	202.1
Liquidambar styraciflua	98.8	13.3 (3)	0.7	275.6
Acer saccharinum	107.5	15.6 (3)	0.7	285.2

*Numbers in parentheses indicate the number of individuals per species burned that achieved an internal temperature above 60°C.

bark. The species that achieved the highest external temperature (*F. americana*, *J. nigra*, and *P. deltoides*) are also the species having bark that ignited during the burn. Some lower external temperature readings were probably caused by wind shifting flames away from the surface probe.

Determination of Bark Physical Properties

Among bark samples taken from the eleven species at the Illini Forest Plantations, analysis of variance yielded highly significant differences (p>0.01) among species for the ratio of dbh to bark thickness, moisture content, specific gravity, thermal conductivity, volatile matter content, time till 300°C ignition, and time till 600°C ignition (Table 4). Seasonal differences in bark moisture content of the two species were not statistically significant.

Table 4.—Analysis of variance for bark thickness/dbh ratio, percentage of moisture content, specific gravity, thermal conductivity, percentage of volatile matter, time till 300°C ignition, and time till 600°C. Number in brackets is the R2 value for the statistical model where significant at the 1% level.

Source of variation	Degrees of freedom	Mean squares for						
		Bark thick./ DBH	Moisture content %	Specific gravity (g/cm^3)	[1]Thermal conoduc-tivity	Volatile matter %	Time till 300°C ignition (s)	Time till 600°C ignition (s)
Species	10	0.0037 [.70]	0.1666 [.65]	0.0927 [.79]	1.7628 [.86]	0.0079 [.80]	1275.9485 [.83]	104.4455 [.79]
Error	55	0.0003	0.0164	0.0044	0.0503	0.0004	47.0818	4.9636

[1] 10-4 cal/cm/sec°C

P. deltoides bark proved to be far thicker than that of the other species of similar age in the Illini Forest Plantation plots. *P. deltoides* is a tree which grows more rapidly than the other species in this study, and whose bark is accordingly thicker because it has greater rates of bark thickening with radial stem growth (Figure 8). In fact the ratio of bark thickness to tree stem dbh and the rate at which bark thickness increases with increasing stem diameter for *P. deltoides* are relatively high among the tree species in this study. *P. serotina* was a volunteer species on the site and therefore had the smallest diameters and the thinnest bark. However, the bark thickness to dbh ratio for *P. serotina* was not the lowest among the species studied (Table 5). Bark thickness was found to be negatively correlated with both specific gravity and thermal conductivity (Table 6).

Moisture content and specific gravity may influence heat transfer to the cambium by bark (Hare 1965, Spalt and Reifsnyder 1962). Bark specific gravity, based on dry mass, showed a tendency toward higher values for species with thinner bark. Among the hardwood species in this study, *P. serotina*, *A. saccharinum*, and *P. occidentalis* had the highest values. *L. styraciflua*, *L. tulipifera*, and *P. deltoides* were low in specific gravity. Values for most of the species fell into ranges found in other studies (Martin and Crist 1968, Spalt and Reifsnyder 1962). Thermal conductivity correlated strongly with specific gravity for all species (Table 6). Specific gravity is a physical property to which other physical and mechanical properties can often be tied (Martin and Crist 1968).

Mean values for percent moisture content were generally lower for thin-bark species (Table 5). (The exception to this trend was *P. deltoides* with the thickest bark and lowest moisture concentration.) The larger proportion of outer bark to inner bark in this species may explain this low percentage. Moisture content of inner bark has been shown to be considerably higher than that of outer bark (Spalt and Reifsnyder 1962, Vines 1968). Therefore, the moisture content of thick-barked *P. deltoides* would be expected to be low with whole-bark analysis. *Q. macrocarpa* had an increase in bark moisture during July, followed by a drop in October (Table 7). This increase may be due to an abnormally rainy month combined with deeply furrowed texture which could easily trap and allow absorbtion of the large amount of rainfall. *A. saccharinum* had smoother bark and exhibited a reduction in moisture throughout the year, as expected. Overall, however, seasonal moisture differences were not significantly different.

The concentrations of volatile material in bark were highest for *L. tulipifera* and *T. americana* and lowest for *Q. macrocarpa*. The high percentage of volatile constituents in the samples might indicate that these barks are easily ignitable, but correlations between volatile matter and time till ignition were not strong (Table 6). Volatile content does not appear to explain differences in peak cambial temperatures during simulated fires nor the amount of time required to achieve ignition, nor did other bark values correlate strongly with volatile matter percentages (Table 6).

Ignition time comparisons revealed that an increase in time was needed for combustion in several species with thinner barks. These species had not only higher specific gravity values overall but also higher peak cambial temperatures. As a result, longer time required for ignition may be due to a more rapid passage of heat to the cambium layer and lower amounts of oxygen available in thinner, high specific gravity bark than in thick-barked species with lower densities. Because glowing combustion will not take place at the surface until temperatures reach 500° to 600°C (Chandler et al. 1983), quicker passage of heat through the bark from the heated surface would increase the time required to reach higher temperatures necessary for ignition. Species with lower thermal conductivity values would hold heat on the surface longer, reducing time until ignition.

SUMMARY AND CONCLUSIONS

The ability of bark to insulate the cambium from lethal temperatures produced by fire is evident in the results of this study. The efficiency of bark varied among species, with thick-barked hardwoods providing as much protection as the conifer *P. strobus*. Diameter of the tree as an indicator of fire resistance was dependent upon the rate of bark thickening with radial stem growth as well as the protective properties of the bark. Upland species tended to be in the high or intermediate

Table 5.—Midsummer bark properties (oven-dry weight basis) of eleven native tree species in a 40-year-old plantation. Means in a column followed by the same letter are not significantly different (a = 0.05).

Tree species	Bark thickness (cm)	Dbh (cm)	Bark thick./ dbh	Moisture content %	Specific[1] gravity (g/cm^3)	Thermal conduc-tivity	Volatile matter %	Time till 300°C ignition (s)	Time till 600°C ignition (s)
Acer saccharinum	0.89de	34.47ab	5.16de	60.53de	0.71ab	3.45a	62.51cd	44b	16b
Fraxinus americana	1.27bcd	33.60ab	7.56bc	90.28b	0.48c	2.33cd	62.24cd	21d	10de
Juglans nigra	1.52b	26.27b	11.57a	81.31bc	0.44cd	2.12d	60.51d	22d	9e
Liquidambar styraciflua	1.10cde	32.17b	6.84bcd	78.74bc	0.44cd	2.13d	60.00d	27cd	5f
Liriodendron tulipifera	1.25bcd	31.90b	7.84bc	106.84a	0.50c	2.39cd	69.79a	32c	14bc
Platanus occidentalis	0.72e	33.00b	4.36e	69.75cd	0.63b	3.05b	61.31cd	49b	20a
Populus deltoides	2.45a	41.50a	11.81a	47.46e	0.45d	2.17d	63.04c	33c	9e
Prunus serotina	0.72e	15.67c	9.19b	62.99de	0.72a	3.45a	61.12cd	26cd	7ef
Quercus macrocarpa	1.36ab	33.57ab	8.10bc	84.69b	0.47c	2.30cd	55.43e	27cd	8e
Tilia americana	1.08cce	32.87b	6.57cd	86.54b	0.51c	2.47c	66.33b	23d	9e
Pinus strobus	0.78e	28.47b	5.48de	87.05b	0.69ab	3.32a	62.26cd	69a	12cd

[1] 10-4 cal/cm/sec°C

Table 6.—Pearson correlation coefficients for properties of eleven native hardwood species from a 40-year-old plantation (n=66).

Bark property	Dbh	Bark thick	Bark thick./ dbh	Moisture content %	Specific gravity (g/cm^3)	[1]Thermal conductivity	Volatile matter %	Time till 300°C ignition (s)	Time till 600°C ignition s)
Dbh	1.0000	0.5949	-0.1164	-0.0705	-0.4303	-0.4071	-0.0127	-0.0241	0.1413
Bark thickness	0.5949	1.0000	0.7042	-0.2688	-0.6614	-0.6464	-0.0869	-0.3385	-0.2397
Bark thick./dbh ratio	-0.1164	0.7042	1.0000	-0.2889	-0.4622	-0.4747	-0.1417	-0.4487	-0.3926
Moisture content	-0.0705	-0.2688	-0.2889	1.0000	-0.1116	-0.2122	0.3680	-0.0640	-0.0415
Specific gravity	-0.4303	-0.6614	-0.4622	-0.1116	1.0000	0.9108	0.0447	0.4931	0.3320
Thermal conductivity	-0.4071	-0.6464	-0.4747	-0.2121	0.9108	1.0000	0.0684	0.5301	0.3861
Volatile matter	-0.0127	-0.0869	-0.1417	0.3680	0.0447	0.0684	1.0000	0.0503	0.1878
Time till 300°C ignition	-0.0241	-0.3385	-0.4487	-0.0640	0.4931	0.5301	0.0503	1.0000	0.5317
Time till 600°C ignition	0.1413	-0.2397	-0.3926	-0.0415	0.3320	0.3861	0.1878	0.5317	1.0000

[1] 10-4 cal/cm/sec°C

Table 7.—Seasonal values of bark properties (oven-dry weight basis) for 40-year-old trees of two species. Means in a column followed by the same letter are not significantly different (a = 0.05).

Tree species	Bark thickness (cm)	Dbh (cm)	Bark thick./ dbh	Moisture content %	Specific gravity (g/cm³)	[1]Thermal conductivity	Volatile matter %
SPRING:							
Acer saccharinum	0.76b	37.33a	4.07b	68.82a	0.76a	3.64a	64.18a
Quercus macrocarpa	1.52a	33.37a	9.11a	62.20a	0.54b	2.59b	56.36b
SUMMER:							
Acer saccharinum	0.89b	34.47a	5.16b	60.53a	0.71a	3.45a	62.51a
Quercus macrocarpa	1.36a	33.57a	8.10a	84.69a	0.47b	2.30b	55.43b
FALL:							
Acer saccharinum	0.73b	34.07a	4.29b	55.90a	0.75a	3.59a	62.40a
Quercus macrocarpa	1.35a	32.53a	8.30a	53.19a	0.46b	2.21b	58.69b

[1] 10-4 cal/cm/sec°C

range for bark thickness to dbh ratios and rate of bark thickening with stem radial growth, while lowland hardwoods tended to have lower ratios.

Cambial temperatures continued to rise after flames went out and while surface temperatures began to drop. Thick-barked species did not reach maximal temperatures as high as those found in species with thin bark. Time required to reach peak temperatures and then return to ambient temperatures increased with bark thickness. *P. deltoides* was the most fire resistant among species of 40-year-old plantation trees tested, perhaps explaining its common presence along streams and minor drainages unprotected from fires in prairie regions of the central United States. *Q. macrocarpa* was also found to be highly fire resistant. *Q. macrocarpa* is a common tree of prairie savannahs, and one that must have been able to survive repeated exposure to intense fires in order to persist in prairie groves frequently exposed to fire. The relatively high resistance of *P. strobus* was expected, as the ability of many conifers occurring in regions with periodic fires to withstand burns is well documented. The high susceptibility of *A. saccharinum* to the heat of fire is consistent with its prevalence in low, moist sites in east central North America where fires probably occurred less frequently.

Specific gravity and thermal conductivity likely affect the amount of heat transmitted to the cambium as well as time required for the bark surface to reach ignition temperatures. Thin-barked species, with higher specific gravity and thermal conductivity values, increased in cambial temperature quickly, while taking longer to ignite. Thick-barked species required more time for heat transfer to the cambium and for cambial heat dissipation.

Considerable volatile material was present in bark samples of all species, but quantity of volatile material was not correlated with maximal cambial temperatures or time until ignition. Overall trends with moisture showed thin-barked species to have lower values. Seasonal testing of *Q. macrocarpa* and *A. saccharinum* revealed no statistically significant difference in seasonal moisture concentration of bark. Bark moisture concentration values were not significantly correlated with any of the thermal properties of bark measured.

Bark properties of hardwoods do exhibit different physical and chemical characteristics that influence the ability of trees to protect cambial tissues from high temperatures. Bark thickness is a good indicator of a tree's ability to protect its cambium from the lethal effects of fire. Thickness in combination with specific gravity strongly influence a tree's fire tolerance. Generally, upland hardwoods tend to produce thicker bark faster than lowland species. However, the bottomland species *P. deltoides* was an exception to this generalization. Both *P. deltoides* and *Q. macrocarpa* exhibit thick bark and relatively high rates of bark thickening with radial growth. These two species have broad ecological amplitudes with respect to substrate moisture and occur further to the west in drier, more fire-prone regions of North America than other eastern deciduous angiospermous trees.

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