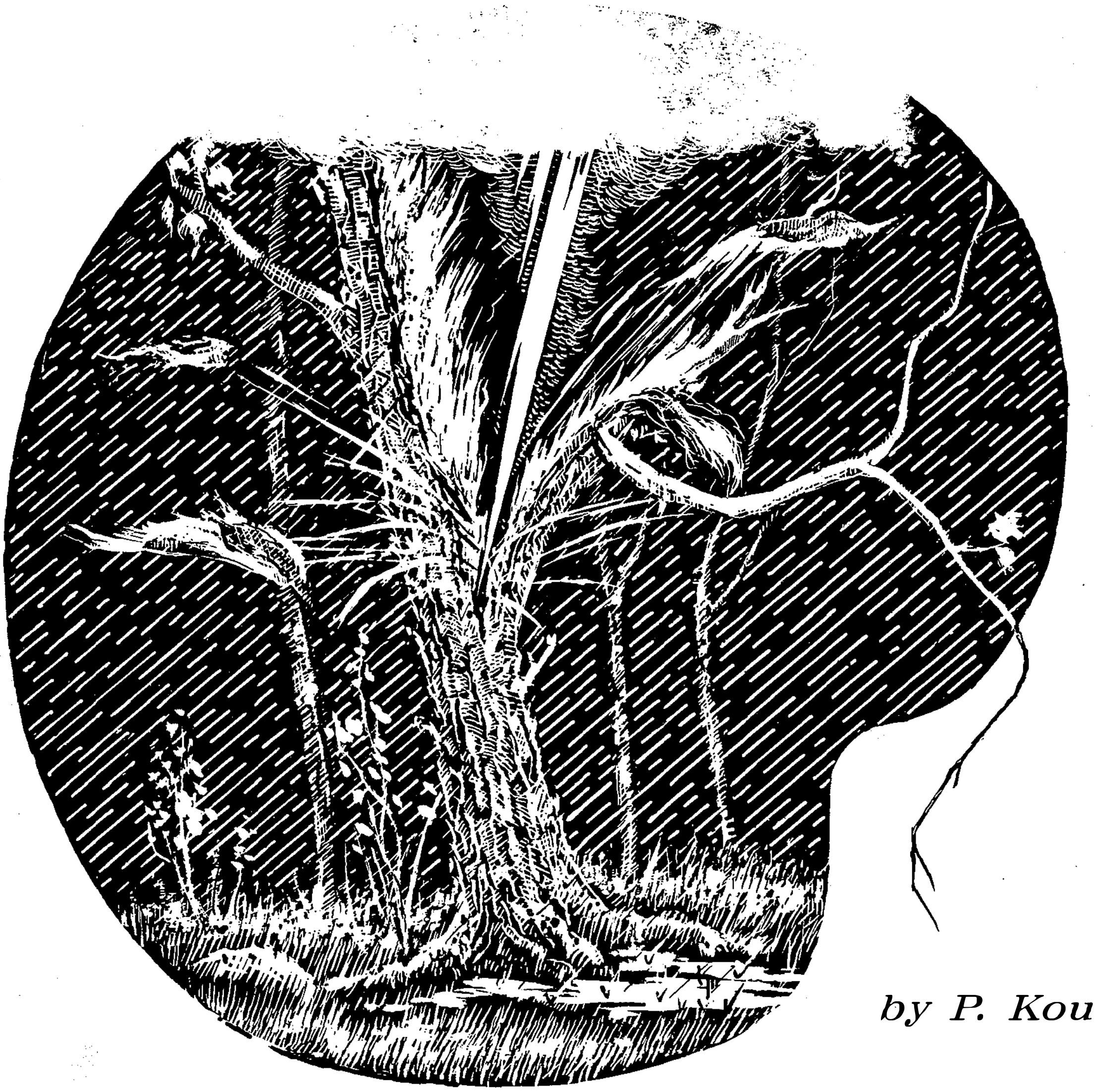
O.D.C. 111.94+426.1(71)

LIGHTNING BEHAVIOUR AND LIGHTNING FIRES IN CANADIAN FORESTS



by P. Kourtz

Sommaire en français

FORESTRY BRANCH

DEPARTMENTAL PUBLICATION NO. 1179 - 1967

CANADA
DEPARTMENT OF FORESTRY
AND RURAL DEVELOPMENT

Published under the authority of
The Honourable Maurice Sauvé, P.C., M.P.,
Minister of Forestry and Rural Development,
Ottawa, 1967

ROGER DUHAMEL, F.R.S.C.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1967

Catalogue No. Fo 47-1179

ABSTRACT

The behaviour and occurrence of lightning and lightning-caused forest fires in the years 1960-63 were studied on the basis of data on 3,615 lightning-caused forest fires. A review of literature indicated that the tree species most frequently struck were the most abundant species having the most favourable characteristics to attract lightning. The nature of the damage depends on the dielectric properties of the tree and on lightning-flash energy.

CONTENTS

LIGHTNING BEHAVIOUR AND LIGHTNING FIRES IN CANADIAN FORESTS

by

P. Kourtz[1]

INTRODUCTION

Lightning fires present a major problem to most forest protection agencies across Canada. Statistics reveal that lightning causes more than 20 per cent of all Canadian forest fires. In 1963 lightning started 48 per cent of all British Columbia's forest fires (Anon., 1960, 1963) and in 1961 started more than 40 per cent of all the forest fires in British Columbia, Alberta and Saskatchewan (Mactavish and Lockman, 1963). Unlike man-caused fires, lightning fires frequently occur in remote, inaccessible areas and often one lightning storm leaves in its path a large number of fires. The British Columbia Forest Service reported that on July 13 and 14, 1960, one electrical storm started 600 forest fires in the Nelson and Kamloops Districts (Anon., 1960, 1963). Only about 60 per cent of the lightning fires are detected within 24 hours after the thunderstorms. The remaining 40 per cent smoulder undetected until burning conditions are favourable for spread.

Even though lightning is an important cause of forest fires, little is known about its behaviour. Only recently have scientists discovered what actually takes place during a light-

[1]Fire Research Officer, Forest Fire Research Institute, Department of Forestry and Rural Development of Canada, Ottawa.

ning flash, and the exact method of charge generation in the thundercloud is still not fully understood. Early forest-protection investigators could find no predictable pattern for the locations of the lightning strikes or for the amount and type of damage caused by lightning to trees.

The Department of Forestry, at the request of the Associate Committee on Forest Fire Protection of the National Research Council, conducted a survey of lightning-caused forest fires across Canada from 1960 to 1963. The aim of the survey was to discover behaviour patterns of lightning and lightning fires so that the phenomenon might be better understood. Lightning-fire reports, Form F958 (Appendix) designed by the Department, were sent to all forest-protection organizations across Canada for completion and return to the Department of Forestry. This paper presents the results of the survey. Thanks are given to government and industrial forest-protection agencies across Canada for their cooperation in the collection of the basic data, without which this paper could not have been written.

RESULTS OF THE SURVEY

Between 1960 and 1963, 3,615 completed lightning-fire reports were returned to the Department of Forestry. The information on each report was transferred to punch cards and analyzed by an IBM data-processing system. The survey dealt only with those flashes that caused forest fires and for this reason its results may not be indicative of normal lightning behaviour. It has been estimated that only about 2 per cent of the trees struck by lightning are ignited (Plumber, 1912).

Type and Condition of Ignited Trees

The survey indicated that 82 per cent of the trees ignited by lightning were softwoods and that 18 per cent were hardwoods; 84 per cent of the ignited softwoods were in pure or nearly pure softwood stands. Of the hardwoods ignited, 53 per cent were in pure or nearly pure hardwood stands and 29 per cent were in pure or nearly pure softwood stands.

There was a relationship between the month of strike and the type of tree ignited by lightning (Table 1).

TABLE 1. TREE TYPE AND MONTH OF STRIKE

Month of strike	Hardwoods ignited	Number in sample
	(Per cent of total for each month)	
May	28.7	171
June	20.7	760
July	19.6	1,183
August	20.3	582
September	24.7	93
October*	45.5	11

*Note the sample size.

A higher proportion of hardwoods were ignited in the spring and fall than in the summer. The reason for this is not understood. Possibly hardwoods are more combustible in spring and fall and/ or softwoods more combustible in summer, or perhaps hardwoods become better lightning conductors in spring and fall.

Fifty-eight per cent of the ignited softwoods, but only 35 per cent of the ignited hardwoods, were green. This indicates that lightning can probably ignite green softwoods more easily than green hardwoods. Thirteen per cent of the hardwoods ignited were classed as rotten and damp compared with only 1.2 per cent of the softwoods. Hardwoods, however, are generally more susceptible to rot-causing fungi (Table 2).

Thirty-eight per cent of the ignited hardwoods, but only 30 per cent of the ignited softwoods, were dry snags. The reason for the difference is not clear. It could have been due to a higher proportion of hardwood snags in the forest or

TABLE 2. TREE TYPE AND TREE CONDITION

	Softwood	Hardwood
	(Per cent)	(Per cent)
Alive - no foliage	6.7	6.7
Green	58.4	34.5
Snags	29.7	38.0
Hollow	3.6	6.9
Rotten and damp	1.2	13.2
Other	0.4	0.7
Total	100.0	100.0

possibly to a difference in ignition characteristics between the two types. More likely it was due to a difference in characteristics favourable to the attraction of lightning — quite likely to a difference in height and crown width.

Further analysis revealed that 31.1 per cent of all the trees that were ignited by lightning were dry snags, and probably only about 5 per cent of the trees in the forests across Canada are dry snags. This suggests either that snags attracted more lightning flashes or that, when struck, they were more easily ignited than green trees. Although there is no proof, it is not likely that snags attract more lightning than green trees, but it is very probable that dry snags can be ignited more easily than green trees.

On cut-over and burned-over areas, 50 per cent of the lightning fires occurred in dry snags. This high percentage of snag ignitions in these areas indicates the need for snag-felling projects such as those carried out by the British Columbia Forest Service (Figure 1).

Damage Caused by Lightning

The amount of tree damage caused by lightning varied

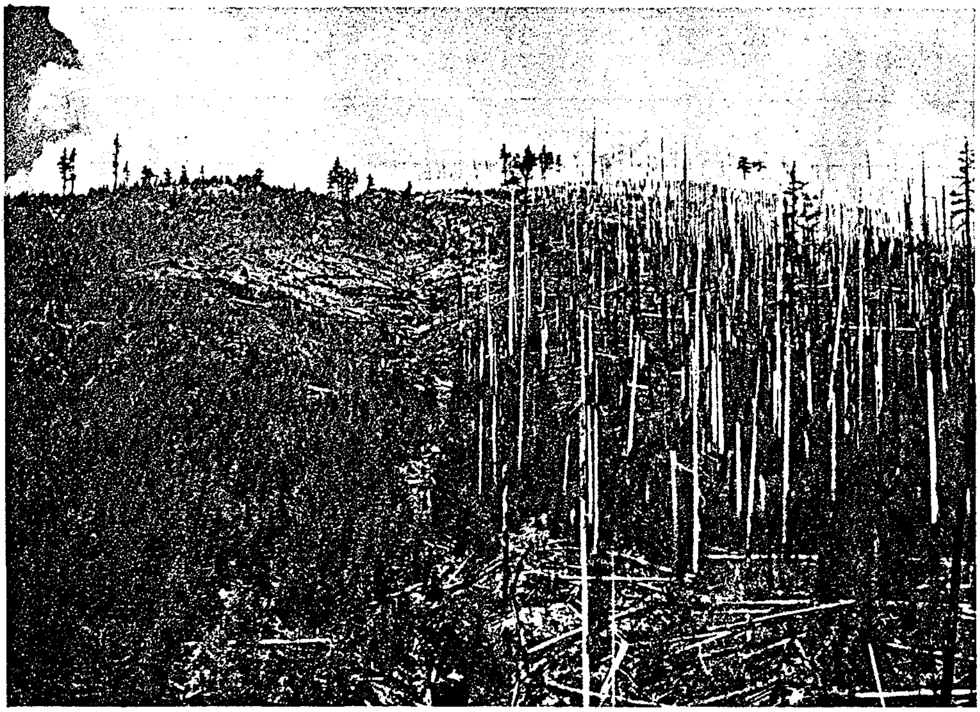


Figure 1. A partly completed snag-felling project in British Columbia.—Courtesy, B.C. Forest Service.

widely. Of 3,320 trees reported struck and ignited by lightning in Canada between 1960 and 1963, 24 per cent were split, 22 per cent were shattered, 27 per cent were grooved, and 20 per cent showed no visible evidence of lightning strikes.

Heights of Trees Struck by Lightning

Forty-five per cent of the trees struck were higher than the surrounding trees, 43 per cent were even with the surrounding trees, and 12 per cent were lower than the surrounding trees. Seventeen per cent of the snags struck were lower than the adjacent trees, but only 8 per cent of the green trees were lower than the adjacent trees. As mentioned previously, lightning apparently can ignite snags more easily than it can green trees, and this probably accounts for the difference. No meaningful differences were found in the relative heights of trees struck at different positions on hillsides. As shown in Table 3, tree height and soil moisture were not related.

TABLE 3. RELATIVE HEIGHTS OF TREES STRUCK AND SOIL MOISTURE

Soil condition	Higher	Even	Lower
	(Per cent)	(Per cent)	(Per cent)
Moist	36	34	39
Dry	62	64	58
Other	2	2	3
Total	100	100	100

<u>Influence of Elevation on Strike Location</u>

The survey results confirmed the popular conception that lightning often strikes high points. Sixty per cent of the strikes were within the top third of the hills, 19 per cent were within the middle third, and 21 per cent were within the lower third. No relationship appeared between location of strikes on hills and type of trees struck.

<u>Influence of Soil on Strike Location</u>

Table 4 shows the relationship between soil moisture and tree type.

TABLE 4. SOIL MOISTURE AND TREE TYPE STRUCK

Soil condition	Softwoods	Hardwoods
	(Per cent)	(Per cent)
Moist	32.9	43.4
Dry	63.9	54.9
Other	3.2	1.7
Total	100.0	100.0

A higher proportion of hardwoods than softwoods were ignited on moist soil. However, hardwoods generally prefer moist soils, and therefore the difference may not be significant. The dryness of the soil appears to be a factor in the ignition of trees by lightning, but the reason for the relationship is not known. Quite likely in the areas of dry soil there were dry fuels, but the dry soil may also have changed the characteristics of the lightning flashes.

Times of Strikes

Table 5 gives the numbers and percentages of fires ignited by lightning at various times throughout the day.

TABLE 5. IGNITION TIME OF LIGHTNING FIRES

Time (Hours)	Number of fires	Per cent
0031 - 0430	311	10.2
0431 - 0830	205	6.6
0831 - 1230	304	9.8
1231 - 1630	1,029	33.4
1631 - 2030	819	26.5
2031 - 2430	415	13.5
Total	3,083	100.0

Seventy per cent of the lightning fires were started between 12:00 noon and 10:00 in the evening, and 84 per cent were started between 6:00 in the morning and 10:00 in the evening — i.e., during a period that includes most of the daylight hours.

Lightning-fire occurrence varied from month to month, from province to province and from year to year. Across Canada, 5 fires were reported in April, 12 in October and 1 in November in 1960-63. In 1962, in Ontario, 11.2 per cent of the fires occurred in May, and in 1963 only 1 per cent occurred in that month. In 1960, also in Ontario, 68.7 per cent of the lightning fires occurred in July, and in 1961 only 32.4 per cent occurred in July. Similar variations were observed for the other provinces. The unpredictable occurrence of lightning fires indicates that forest-protection agencies must be prepared for a large number of lightning fires throughout the entire fire season.

<u>Times of Discoveries</u>

The survey reports gave the discovery times of lightning fires as shown in Table 6.

TABLE 6. DISCOVERY TIMES OF LIGHTNING FIRES

Discovery time	Number of fires	Per cent of total
(Hours)		
0031 - 0430	20	0.6
0431 - 0830	165	4.8
0831 - 1230	660	19.2
1231 - 1630	1,642	47.6
1631 - 2030	831	24.2
2031 - 2430	124	3.6
Total	3,442	100.0

From this table it can be seen that nearly half of the lightning fires were discovered between 1231 and 1630 hours, and also that more will be gained by having the towermen up later in the evening after the storm than earlier in the morning of the following day.

Table 7 gives the elapsed times from strike to discovery.

It is interesting to note the elapsed-time distribution pattern. A large percentage of fires were detected shortly after strikes, but the detection of the remaining fires required many days. On the average, five days after the storm

TABLE 7. ELAPSED TIME AND DISCOVERY PERCENTAGES

Elapsed time to discovery	Fires discovered	Cum. per cent discovered	Per cent not discovered
(Hours)	(Per cent)		
0 - 4.5	29.9	29.9	70.1
4.6 - 8.5	4.8	34.7	65.3
8.6 - 12.5	4.7	39.4	60.6
12.6 - 16.5	6.2	45.6	54.4
16.6 - 20.5	7.4	53.0	47.0
20.6 - 24.5	6.6	59.6	40.4
2 days*	22.5	82.1	17.9
3 days	6.7	88.8	11.2
4 days	3.1	91.9	8.1
5 days	2.4	94.3	5.7
6 days	1.7	96.0	4.0
7 days	1.1	97.1	2.9
8 days	0.6	97.7	2.3
9 days	0.8	98.5	1.5
10 days	0.4	98.9	1.1
11 days or more	1.1	100.0	0.0

*Note change in scale.

5.7 per cent of the fires were yet to be discovered. No doubt the reason for this delay in discovery was partly the influence of darkness, especially during the first 24 hours after the strikes. However, this factor would not be important over a period of several days.

Table 8 shows time of strike and elapsed time to discovery. Of the strikes occurring between 1131 and 1830 hours, 32.2 per cent were discovered within the first hour. Presumably this was mainly because of favourable burning conditions during the afternoon. Of the strikes occurring between 1831 and 1130 hours, only 8.8 per cent were detected within one hour after the strikes.

TABLE 8. TIME OF STRIKE AND ELAPSED TIME TO DISCOVERY

Time of strike	No. of fires discovered within 1 hour after strike	Total No. of strikes	Per cent of total
(Hours)			
1131 - 1830	489	1519	32.2
1831 - 1130	137	1564	8.8

Fifty-one per cent of the lightning reports stated that more than one-tenth of an inch of rain fell. To examine the effect of the amount of rainfall on the delay in discovery, the reports were listed by elapsed times to discoveries and by corresponding amounts of rainfall.

From Table 9 it can be seen that elapsed times were not influenced by the amounts of rain that fell during the storm; the rainfall data in most cases were probably taken at weather stations nearest the strikes. Weather stations are often 20 miles or more apart, and most thunderstorms are only a few miles in diameter. Therefore, rainfall observations for many of the storms would not be applicable to the stroke area. One important conclusion can be made from these observations: detection systems should not be relaxed just because weather stations in the storm vicinity record large volumes of rain.

When the Drought Indices at the time of discovery of each fire were compared with the corresponding elapsed times, no relationship existed. This perhaps should have been expected, since more than 60 per cent of the reports indicated that the first fuels ignited were fine fuels consisting of duff, moss and grass. The Drought Index is a measure of the dryness of the larger fuels. Like the rainfall data, the Drought Indices were determined at the closest weather stations and therefore may not be representative of the areas adjacent to the lightning strikes.

TABLE 9. AMOUNT OF RAINFALL AND ELAPSED TIME TO DISCOVERY

Elapsed time to discovery	Greater than 0.1 inch of rain	Cumulative per cent	Less than 0.1 inch of rain	Cumulative per cent
(Hours)	(No. of fires per cent)		(No. of fires per cent)	
0 - 4.5	28.1	28.1	28.1	28.1
4.6 - 8.5	4.5	32.6	4.2	32.3
8.6 - 12.5	4.6	37.2	4.9	37.2
12.6 - 16.5	5.8	43.0	6.0	43.2
16.6 - 20.5	5.4	48.4	8.9	52.1
20.6 - 24.5	6.4	54.8	6.6	58.7
2 days*	23.1	77.9	23.2	81.9
3 days	7.7	85.6	6.6	88.5
4 days	3.6	89.2	3.1	91.6
5 days	3.4	92.6	3.0	94.6
6 days	2.3	94.9	1.1	95.7
7 days	1.1	96.0	1.2	96.9
8 days	0.8	96.8	0.7	97.6
9 days	1.0	97.8	0.8	98.4
10 days	0.4	98.2	0.6	99.0
11 days or more	1.8	100.0	1.0	100.0

*Note scale change.

The Danger Index is a good indicator of the dryness of the fine fuels. As seen in Table 10, some relationship was found between the Danger Indices before the storm and at the time of the discovery of each fire and the times required to discover the fires.

The elapsed times to discoveries varied widely from province to province. Over the four-year period two provinces discovered 7 per cent of their lightning fires within the first hour after the strike, while two other provinces discovered 30

TABLE 10. ELAPSED TIME AND DANGER INDEX

	Danger Index before storm		Danger Index at time of fire discovery	
	(Below 12)	(12 or above)	(Below 12)	(12 or above)
Per cent of fires discovered within 5 hours after strike	28	33	27	35

per cent of their lightning fires within one hour after the strike. This difference was quite significant and even after the times of strike were considered there still was an appreciable difference. The reasons for this difference require further investigation.

LITERATURE REVIEW

The better to understand the behaviour and occurrence of lightning and thus be in a better position to assess the field observations, a literature review of the work that has been carried out to date on this subject was undertaken.

Formation of a Lightning Flash

In a thundercloud, positive and negative charges are formed on cloud particles. These charged particles are separated, the positively charged particles rising to the top of the cloud and the negatively charged particles moving to the base. This separation of charges is associated with the formation of precipitation-sized droplets at below-freezing temperatures. Many theories have been proposed to explain the mechanism of charge separation, but the exact reason is not fully understood (Malan, 1963).

The large negative charge formed at the base of the cloud induces positive ions to leave pointed, conducting objects on the ground. These ions are carried aloft by strong updrafts that accompany the thunderstorm and collect in unevenly distributed pockets beneath the thundercloud. The path of the lightning flash is greatly influenced by these positively charged pockets.

When the electrical charge in the cloud reaches a critical level, streams of electrons leave the base of the cloud and proceed toward the ground. The downward discharge from the cloud to the ground is known as a leader stroke. The initial leader stroke leaving the cloud does not progress continuously but descends earthward in a series of steps approximately 60 feet long with pauses between steps of about 50 microseconds. The direction of the stepped leader is influenced by the pockets of positively charged ions, which cause it to fork or to follow a very irregular route to the ground.

As the tip of the stepped leader approaches the ground, a strong induced positive charge is concentrated in the ground beneath. Just before the leader reaches the ground, positive streamers leave the better conducting points on the ground and proceed toward the leader tip. The first streamer that reaches the leader tip determines the path of the flash (Malan, 1963). Streamers 8 feet in length have been photographed (Lewis, 1950).

At the time of the contact between the stepped leader and the positive streamer a return stroke of positive charge from the ground immediately travels up the ionized leader channel, neutralizing the negative charge in it. Since all the charge in the cloud may not be dissipated by the first stroke, others may follow within a few hundredths of a second. Each succeeding stroke is initiated by a dart leader, which travels from the cloud, without pausing, down the ionized path of the original stroke directly to the ground, ignoring the branches formed by the first stroke. A return stroke from the earth again flows up the dart channel, neutralizing it. Up to 14 different strokes in one flash have been photographed (Malan, 1963). The average number of strokes per flash varies. In England most flashes have one stroke while in South Africa most have four.

The current in the return stroke rapidly increases to a peak value, as high as 200,000 amperes in extreme cases, and then gradually drops to a lower value that is often only a few hundred amperes. Even though the current peak of a stroke may be 100,000 amperes, its duration may be too short to involve more than a few coulombs (Beck, 1954). Investigators found that 50 per cent of flashes had a duration of 0.3 seconds while the maximum duration noted was 1.5 seconds (Lewis, 1950). Only about 5 per cent of flashes lasted 0.7 seconds or more. Five per cent of flashes generated 120,000 amperes or more while 50 per cent of flashes generated 25,000 amperes or less (Bewley, 1951).

Damage Caused by Lightning

Apart from damage by fire, lightning alone causes a significant amount of damage to forest trees. Wadsworth (1943) stated: "It accounts for about one-third of the total timber mortality in the ponderosa pine forests of northern Arizona and in addition causes a considerable amount of defect." Lightning may strike a tree, leaving no visible evidence, or it may shatter a tree. It may wound a tree, leaving it exposed to fungi and insects, or it may cause the tree to form abnormal tissue similar to frost rings in the interior (Von Tubeuf, 1906) (Figure 2). Lightning has been known to kill large groups of trees even though no tree showed signs of being struck (Boyce, 1948).

Many theories have been proposed to explain how lightning causes such a variety of damage to trees (Figures 3 and 4). Around 1900, it was felt that the direction of the flash

DAMAGE CAUSED
BY LIGHTNING

Figure 2. (Top left) Evidence of disease resulting from a lightning wound in a sugar maple.

Figure 3. (Above) A strip of bark removed by lightning.— Courtesy, B.C. Forest Service.

Figure 4. (Left) A tree decapitated by lightning.

determined whether or not the tree was heavily damaged (Plumber, 1912). The direction of the flash was supposedly determined by the type of charge in the tree. Early European investigators suggested that sound wood passed the electricity rapidly to the ground without much physical damage (Fisher, 1895). Damage resulted when lightning struck rotten wood, since rotten wood was assumed to be a poor conductor. Many observations have shown that their theory is not correct, since sound green trees are often heavily damaged. Later, to explain the splitting and grooving of the bark, it was suggested that lightning required an open channel for its passage and therefore mechanically split the tree (Plumber, 1912). This idea was rejected when microscopic examinations of fragments from wound areas revealed that lightning produced no visible evidence of torn tissue, as would be expected had the tissue been mechanically separated. The most widely accepted theory of how trees are damaged is that the lightning current travels up the most moist part of the tree, producing superheated steam under high pressure that ruptures the bark. This theory does not explain how lightning shatters trees (Dorsey, 1927). However, the path of least resistance in a tree is determined not by the amount of water but by the mineral content of the water. It is likely that in some cases the mineral content of heartwood moisture is higher than that of sapwood moisture and that the path of least resistance is thus in the heartwood. If this is so, it explains the shattering of trees.

The extent of damage caused by lightning to trees is probably determined by the energy (intensity and duration) of the return stroke and by the trees' conductive properties. Beck (1954) stated: "It has been observed and corroborated by laboratory tests that the high current peaks are destructive in that they are very likely to cause physical damage, such as the shattering of trees or wood poles or masonry, but that they will not set fires. The low-current long duration portion of the stroke, when it occurs, is not disruptive, but will ignite flammable material. Lightning current flowing in a good conductor produces no power to injure the conductor. If it flows in a high resistance medium, such as a tree, a wood pole, or a brick chimney, high voltages develop, watts are produced and disruptive effects or fire may occur."

If the outside of a tree were well soaked with rainwater, a short-duration, high-intensity current would pass up it without entering the interior. If the bark of the tree were rough, the path of water to the ground would perhaps not be continuous and thus the current would be forced to seek a new path of lower resistance — the moist interior of the tree. A long-duration current would evaporate a continuous path of water on the bark. The current would then travel in the interior of the tree.

Ross (1947) stated that dust on hydro insulators greatly affects the conducting properties of rainwater on these insulators. The dust contains salts that make water a much better conductor. The same phenomenon could happen on the surface of trees. If, however, prior rain removed the dust, the rainwater from the thunderstorm might be a relatively poor conductor, thus causing the current to enter the interior of the tree.

Dry snags are very poor conductors of electricity, but rainwater may make them excellent conductors. Lusignan and Miller (1940) stated: "During a rainstorm, the lightning insulation strength of structures utilizing wood as supplementing insulation may suffer reductions to as low as 65 per cent of the dry flashover voltage within two or three minutes after the start of rainfall; further reduction with continuation of the rain is inappreciable." Also, Ross (1947) stated that resistance of a 10-per-cent-moisture-content wood surface will be reduced in the order of 1,200 or 1,400 to 1 simply by wetting the surface. A high-energy stroke, however, would evaporate surface moisture, thus greatly increasing the resistance and causing the snag to ignite. In the case of a green tree, once the surface water had been evaporated, the current would travel in the interior without igniting the tree, provided the current was of low intensity and short duration.

After 200 laboratory tests, Ross (1947) concluded that on a wet wooden pole a dry surface area that was in series with the flow of electricity could cause a fire. He further concluded: "This dry area, being high in resistance in comparison with adjacent series wetted wood surfaces, results in a voltage concentration across the dry zone. If the dry zone is sufficiently short for a given circuit voltage, electrical breakdown occurs across the dry zone. This electrical breakdown being located favourably in dry wood and encouraged by a breeze, may result in a pocket burn." Ross's tests were with long-duration, high-voltage currents carried on hydro lines, but the same conclusions should apply for rain-dampened snags or snags that contain pockets of moist rotten wood.

Locality of the Strike

Influence of Height

From the previous description of the physics of lightning it can be seen that height is an important factor in determining which tree will be struck. Height, however, is not the only criterion: the tree must also be a good conductor. If the highest tree is not the best conductor, a lower, better-conducting tree may be struck.

According to the theory of lightning protection, the area under a 45-degree conical surface whose tip is an earth conductor will be protected from lightning (Anon. 1952). Anything that projects outside the 45-degree cone may be struck. The theory also states that the area beneath a cone of 22½ degrees has a high probability of not being struck. This rule can be applied to good conducting trees (Figure 5).

An isolated tree on flat ground would probably attract

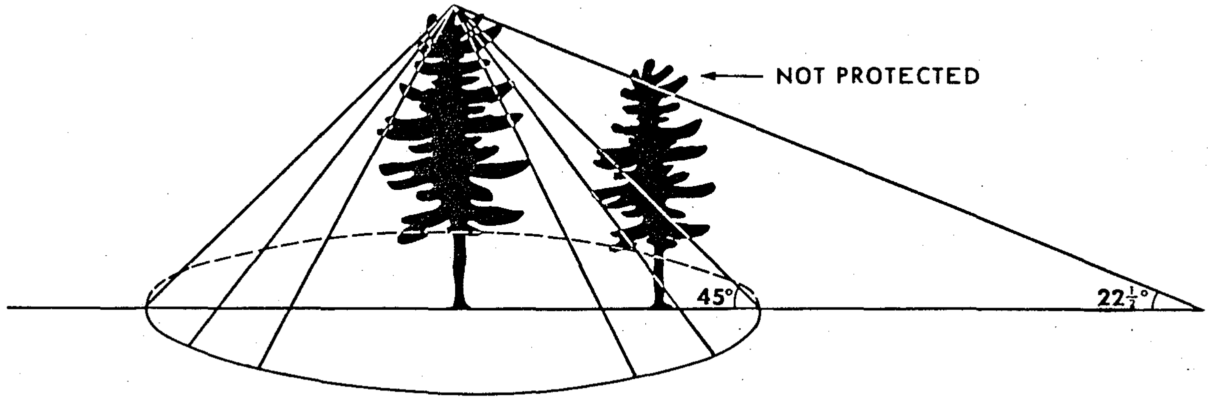


Figure 5. Area protected by a good conducting tree.

all flashes within a radius of twice its height provided it were a good conductor. It may be concluded that the chance of a given tree's being hit in the open is much greater than if the same tree were in a forest, but the number of strokes to a square mile of open field will be the same as the number of strokes to a square mile of dense forest.

From an isokeraunic map (Longley, 1952) showing the annual average of thunderstorm days, it may be seen that the Sioux Lookout area of Ontario will have approximately 30 thunderstorm days per year. According to Beck (1954) there is a high probability that an isolated mast 275 feet high will be struck once a year in an area where the isokeraunic level is about 30. Therefore, an isolated good conducting tree 90 feet high on flat ground near Sioux Lookout will be struck, on the average, about once every three years.

Influence of Elevation

According to the theory of lightning protection, a good conducting hilltop will attract those flashes that fall within its zone of attraction (Malan, 1963). The area of this zone depends on the height of the hill above the surrounding country. As stated previously, the Department of Forestry survey indicated that 60 per cent of the strikes fell within the top third of the hill. However, a surprisingly large number of trees (21 per cent) were struck in valleys that were presumably within the zone of attraction of the tops of adjacent hills. Malan (1963) suggested that in these cases the hilltops may be composed of materials that act as insulators while the moist valley soils act as conductors.

Influence of Soil

The influence of soil on the location of lightning strikes has been investigated by the Europeans several times, and the resulting reports stated that a high percentage of trees were struck on loam soils (Fisher, 1895; Ruedy, 1945). It is doubtful, however, if these findings were weighted by the proportions of soil types in the area under study. The number of lightning flashes striking an area is probably influenced mainly by soil moisture rather than by soil type. Ruedy (1945) investigated the resistivity of various soil types at various moisture contents. His investigations revealed that dry loam is a better conductor than dry sand and that moist soil is a much better conductor than dry soil. Also, he found that the conductivity of moist soil varies widely depending on the mineral content of the soil water. Beck (1954) stated: "In regions where rock formations of great age are near the surface, the earth's resistivity is usually high because even though the rock may be porous and hold moisture, soluble salts have been leached away throughout the ages. There is some evidence that, in regions of high soil resistivity, there is a greater likelihood that currents of long duration will prevail. In such areas, the neutralizing current must pass through high resistance, thus decreasing its magnitude and lengthening its duration, like discharging a capacitor through high resistance." This, along with the fact that dry fuel would accompany dry soil, explains why so many lightning-caused forest fires start on dry soil.

Influence of Air Conductivity

European investigators studied the conductivity of air during fair weather in areas frequently struck by lightning and in areas never known to be struck by lightning (Ruedy, 1945). They found that the conductivity of the air was permanently high at spots frequently struck and that at points rarely struck it was permanently low. Later investigators, however, showed that air conductivity varied widely throughout the day depending on the time the measurement was taken.

Over most areas air movement takes place and thus ionized air is moved. Because of this, it seems highly unlikely that the air over one area can be permanently more conductive than air over adjacent areas.

Susceptibility of Species

Whether one species is more susceptible to lightning than another has been a controversial question for many years. Many early European investigators were convinced that certain species were more susceptible (Fisher, 1895), but early American investigators were convinced that this was not so (Plumber, 1912).

From an investigation carried out in similar French and German forests it was concluded that if each species was present in equal numbers, for every one beech tree struck, 55 oak, 6 spruce and 37 pine would be struck (Plumber, 1912). Further proof of the immunity of beech was presented by Janesco Dometric of Germany, who tested the electrical conductivity of wood species. He concluded: "The use of heartwood or sapwood and state of dryness of the wood made no difference in the results, but the richness of beech in oil prevents its being a good conductor" (Fisher, 1895).

On the basis of the results of an investigation of a large number of lightning strikes in the western United States between 1905 and 1912, Plumber (1912) drew the following conclusion: "Any kind of tree is likely to be struck by lightning and the greatest number struck in any locality will be the dominant species." Experiments by the United States Forest Service showed that the electrical conductivity of wood was related to the moisture content of the wood and not to the species of the wood; however, heavy rain could wet any tree so that it would temporarily become an excellent conductor (Plumber, 1912).

From the previous discussions on the behaviour of lightning it may be concluded that the probability of lightning striking a particular tree could be expressed as some function of the tree's height and conductivity. Tree species differ in site preferences and heights at maturity. A dominant species that prefers upland sites will be struck more often than an intermediate species that prefers lowland sites.

Some early European reports suggested that the reason for the partial immunity of beech and birch was the characteristic of their bark (Moorehouse, 1939). Beech and birch both have smooth bark, and it is thus possible for them to have a continuous sheath of water down their trunks which would conduct electricity from the ground without causing visible damage. Therefore, beech and birch may be hit as often as other species, but no visible damage results from the strikes.

Lightning-fire Zones

It has been recognized for many years that zones of lightning fires exist. Many lightning-fire zones have been mapped by forest-protection agencies, which have used them to improve their detection and suppression systems (Bennett, 1958). The reason why these lightning-fire zones exist is not clear. At first one might assume that they exist because of a concentration of lightning strikes. This may be only part of the answer. As stated previously, there seems to be a definite relationship between the moisture content of the soil and the number of lightning fires. There is also a relationship between the conditions of trees and the number of fires. Over a large area, therefore, if there were many snags and if the soil were well drained, a lightning-fire zone might be recognized. If its existence were proven, selected snag felling in immature and mature forest stands in lightning-fire zones solely for the reduction of lightning fires might be economical.

Lightning-fire Occurrence and Rainfall

Gisborne (1931) reported that records from groups of national forests in the western United States showed that 92 per cent of the thunderstorms were accompanied by rain and that on the average it rained for 12 minutes before the lightning and for 37 minutes after the lightning. Further investigations revealed that storms that started fires had a consistently lower average rainfall before and after the lightning than storms that didn't start fires. Eight per cent of the 14,754 thunderstorms investigated delivered no rain. One-third of these storms started fires, but one-third of the storms accompanied by rain also started fires. "This close similarity refutes the popular conception that dry storms as a class are more dangerous than wet storms" (Gisborne, 1931).

Devices That Warn of Approaching Thunderstorms

One of the simplest devices that warns of approaching thunderstorms consists of an aerial connected to the ground through a microammeter (Malan, 1963). The microammeter may be replaced by an amplifier and loud speaker that give audible warning, the loudness increasing as the storm approaches. This device detects approaching storms up to 12 miles away, but problems are encountered in estimating the distance to the thunderstorms since storms of different sizes produce different electrical-field strengths.

There are more complex electromagnetic radiation detection devices available that, when used with radar, provide effective means of distinguishing electrical storms.

Tracking of Thunderstorms

To improve detection efficiency and reduce the cost of detecting lightning fires the paths of the storms should be known. Expensive electronic equipment is now available that can provide enough information to permit accurate mapping of thunderstorm paths. By using two stations and triangulation, the location of one or more storms can be determined for distances up to 200 miles.

Lookout networks are maintained by most forest-protection agencies and since, according to the lightning survey, 84 per cent of the storms that start fires occur during the daylight hours, adequate warnings of approaching storms and their paths could be given by lookout observers. Morris (1934) described a successful technique to map the paths of thunderstorms on the basis of lookout reports.

Lightning Strike Locating Devices

Devices are now being perfected to distinguish between a cloud-to-cloud and a cloud-to-ground flash and to locate where each flash strikes the ground (Malan, 1963). These devices show promise for forest-protection use. Since about 2 per cent of the flashes start fires (Plumber, 1912), these devices, to be of practical use, must be modified to locate only the strikes that may cause fires. This could possibly be done by making them sensitive only to the long-duration, high-intensity flashes.

Thundercloud Modification

The United States Forest Service is currently conducting an ambitious project to determine whether and how thunderstorms can be modified so that lightning fires can be reduced or eliminated. Project "Skyfire" has been going on since 1953, but so far no conclusive evidence has been presented that lightning fires can be reduced through cloud-modification techniques. Experiments in 1960-61 indicated that cloud modification did reduce the number of lightning strikes to ground by 38 per cent. A statistical analysis revealed that the probability of this difference occurring by chance was about one in four (Fuquay, 1964).

SUMMARY

The survey results, combined with the literature review of lightning behaviour, provide a basis for describing lightning behaviour and lightning fires in Canadian forests.

1. Approximately 80 per cent of the trees ignited by lightning are softwoods.
2. More hardwood snags are ignited than green hardwoods.
3. Hardwood snags seem to be more susceptible to lightning fires than softwood snags.
4. Given a forest stand with an equal number of hardwood and softwood trees, more hardwoods than softwoods will be ignited.
5. A higher proportion of hardwoods are struck in the spring than in the summer; the reason for this difference is not known.
6. Dry snags are very susceptible to lightning fires.
7. The damage caused by lightning and the ignition of a tree depends on the energy (intensity and duration) of the lightning stroke and the dielectric properties of the tree and the soil.

8. Relative height and elevation are important factors determining where lightning will strike. However, the ability of the tree and the soil to conduct electricity is also an important factor.
9. A high proportion of lightning fires occur on dry soil, which would be accompanied by dry fuel. Also on dry soil the duration of the lightning strike may be lengthened and may thus provide more time for ignition.
10. Eighty-four per cent of the lightning fires were started between 0600 and 2200 hours, and nearly half the lightning fires were discovered between 1231 and 1600 hours. More fires were discovered in the late evening than in the early morning.
11. Information taken at weather stations in the storm vicinity cannot be used to predict the number of lightning fires that will be started or when the fires will be discovered.
12. Lightning-fire zones do exist, but the reasons for their existence are not understood.
13. To reduce detection costs and improve detection efficiency the path of each thunderstorm needs to be known. No inexpensive devices to tract thunderstorms accurately are available.

SOMMAIRE

L'auteur, se basant sur des relevés qu'il a faits et sur ce qui a été publié sur le sujet, décrit les feux de forêt causés par la foudre en forêt canadienne et relate le comportement de la foudre par rapport aux divers types de forêt. Voici un résumé de sa compilation:

1. Les arbres résineux forment environ 80 p. 100 de tous les arbres enflammés par la foudre.
2. Parmi les arbres feuillus, la foudre allume plus d'arbres séchés que d'individus feuillés.

3. La foudre semble atteindre plus d'arbres séchés chez les feuillus que chez les résineux.
4. Dans un peuplement mêlé de résineux et de feuillus en nombre égal, l'on verra s'enflammer plus de feuillus que de résineux.
5. Pour cause inconnue, la foudre atteint une plus grande proportion d'arbres feuillus au printemps qu'en été.
6. Les arbres séchés depuis longtemps sont très facilement enflammés par la foudre.
7. La quantité de dommages causés à un arbre varie selon l'énergie (intensité et durée) de l'éclair et selon les propriétés diélectriques de l'arbre et du sol.
8. Quatre facteurs importants qui permettent de prévoir où la foudre frappera sont l'altitude et la hauteur relative de l'arbre, et la conductibilité de l'arbre et du sol.
9. Une forte proportion des feux débutent sur un sol plutôt sec alors que les combustibles sont, eux aussi, secs. De plus, l'éclair peut durer plus longtemps quand le sol est sec et ceci peut favoriser l'ignition.
10. Quatre-vingt-quatre p. 100 des incendies furent allumés entre 6 h et 22 h. Presque 50 p. 100 furent découverts entre 12 h 31 et 16 h. On détecta plus de feux à la fin du soir (avant minuit) et moins plus tard dans la nuit (après minuit).
11. Les informations que l'on obtiendra des stations météorologiques situées près de l'orage ne peuvent servir à prédire le nombre de feux qui seront allumés ni le moment de leur détection.
12. L'on ne sait pourquoi, mais il existe des zones bien déterminées de feux causés par la foudre.
13. Pour améliorer la technique de détection des feux et réduire son coût, il faut connaître la course de l'orage. Malheureusement, il n'existe pas encore d'appareil peu dispendieux qui puisse suivre une telle course avec précision.

REFERENCES

Anon. 1952. Code for protection against lightning. Handbook 46, Bureau of Standards, U.S. Dept. of Commerce.

Anon. 1960. Report of the British Columbia Forest Service.

Anon. 1963. Report of the British Columbia Forest Service.

Beck, E. 1954. Lightning protection for electrical systems. McGraw-Hill Book Co. Inc.

Bennett, W.D. 1958. The control of lightning-caused forest fires. Woodlands Research Index No. 106, Pulp and Paper Research Institute of Canada.

Bewley, L.V. 1951. Travelling waves on transmission systems. Second edition, Wiley, New York.

Boyce, J.S. 1948. Forest pathology. McGraw-Hill Book Co. Inc.

Dorsey, E.H. 1927. Lightning. U.S.D.A. Monthly Weather Review, Vol. 55, No. 6.

Fisher, W.R. 1895. Forest protection. Schlick's Manual of Forestry, Vol. IV, Bradbury, Agnew & Co., London.

Fuquay, D.M. 1964. Lightning modification research. Intermountain Forest and Range Experiment Station, U.S. Forest Service.

Gisborne, H.T. 1931. A five-year record of lightning storms and forest fires. U.S.D.A. Monthly Weather Review, Vol. 59, No. 4.

Lewis, W.W. 1950. The protection of transmission systems against lightning. John Wiley and Son Inc.

Longley, R.W. 1952. Thunderstorm data for Canada. Circ. 2159, TEC-121, Meteorol. Div., Dept. of Transport, Canada.

Lusignan, J.T. and C.J. Miller. 1940. What wood may add to primary insulation for withstanding lightning. American Institute of Electrical Engineers, Vol. 59.

Mactavish, J.S. and M.R. Lockman. 1963. Forest fire losses in Canada - 1962. Canada Dept. of Forestry, For. Res. Br., Ottawa.

Malan, D.J. 1963. Physics of lightning. University of the Witwatersrand, Johannesburg, The English Universities Press Ltd., London.

Moorehouse, S. 1939. Trees and lightning. Wood. July.

Morris, W.G. 1934. Lightning storms and fires on the national forests of Oregon and Washington. Pacific Northwest Forest Experiment Station, U.S. Forest Service.

Plumber, F.G. 1912. Lightning in relation to forest fires. U.S. Forest Service Bulletin 111.

Ross, P.M. 1947. Burning of wood structures by leakage currents. American Institute of Electrical Engineers, Vol. 66.

Ruedy, R. 1945. The distribution of thunderstorms and the frequency of lightning flashes. National Research Council, Ottawa, No. 1282.

Tubeuf, C. Von. 1906. Beobachtungen über elektrische Erscheinungen im Walde. VII. Uber sogenannte Blitzlöcher im Walde. Naturiv Ztschr. Land. u. Forstiv. 4:344-351.

Wadsworth, F.H. 1943. Lightning damage in ponderosa pine stands of northern Arizona. Journal of Forestry 4:684-685.

1179-6-67-3M

APPENDIX

LIGHTNING FIRE REPORT

(One copy to be submitted for each fire classified as lightning caused)

Province or Protection Organization..

District............................ Sub Dist. or Div. ....

Fire Report No. .... Date .... 19.... Name of fire ....

Location .... Area When Controlled .... acres
(Lot, Range, Township, Lat. and Long., or other designation)

	Answer is: Known	Answer is: Estimated
Time of Strike: Date .... Hour		
Time Fire Discovered: Date .... Hour		
Evidence of lightning strike:		
A tree was: Split ☐ ; Shattered ☐ ; Grooved ☐ ;		
Ground was disturbed ☐ ; Thunderstorm reported in area ☐ ;		
Other evidence (describe)		
Forest type in area of strike:		
All Conifers ☐ ; All Hardwoods ☐ ; Cut-over ☐ ;		
Mostly Conifer ☐ ; Mostly Hardwood ☐ ; Old burn ☐ ;		
If lightning struck a tree, was it:		
Conifer ☐ ; Hardwood ☐ ;		
Higher than ☐ ; Even with ☐ ; Lower than ☐ , surrounding trees		
Alive, with no foliage ☐ ; Green, with leaves ☐ ;		
Dead: Sound and dry ☐ ; Hollow ☐ ; Rotten and damp ☐ ;		
Other, (describe)		
Fire first occurred in:		
Branches ☐ ; Trunk ☐ ; Roots ☐ ;		
Surface fuels: At base of tree ☐ ; Away from tree ☐ ;		
Specific fuel first ignited:		
Bark ☐ ; Duff ☐ ; Grass ☐ ; Twigs ☐ ; Moss ☐ ; Other ☐ ;		
If lightning did NOT strike a tree:		
Describe probable behaviour of lightning and first fuel to catch fire		
....		
....		

Answer is: Known | Estimated

Strike occurred:

At or near a hilltop ☐ ;

On a hillside, within: Top 1/3 ☐ ; Middle 1/3 ☐ ; Lower 1/3 ☐ ;

Slope faces: North ☐ ; East ☐ ; South ☐ ; West ☐ ;

Area where fire occurred is:

In a valley bottom ☐ ; Generally flat ☐ ; Ridged ☐ ;

Gently rolling hills ☐ ; Broken steep hills ☐ ;

Ground condition in area of strike:

Rock outcrop ☐ ; Shallow soil ☐ ; Deep soil ☐ ;

Sand or gravel ☐ ; Loam ☐ ; Clay ☐ ;

Moist ☐ ; Dry ☐ ; Other (describe) ....

Weather conditions at station nearest fire (........ miles, approx.)

(a) Before storm

Weather generally: Sunny ☐ ; Cloudy ☐ ; Warm ☐ ; Cool ☐ ;

Prevailing wind direction: N ☐ , E ☐ , S ☐ , W ☐ ,

Danger index ...... Drought index ...... day before storm

(b) On day of thunderstorm:

Sky was mainly: Clear ☐ ; Variable clouds ☐ ; Overcast ☐ ;

Air was: Clear ☐ ; Hazy ☐ ; Very hazy ☐ ;

Visibility (miles): Over 15 ☐ , 6-15 ☐ , Less than 6 ☐

Storm was accompanied by rain 0.10" or more: Yes ☐ , No ☐ ,

Thundercloud came from: N ☐ , E ☐ , S ☐ , W ☐ ,

(c) On day of fire

Danger index .... Drought index ....

Weather Observations at Fire: (Time.........)

Temperature....°F, Relative Humidity....%, Wind Velocity....mph.

Wind Direction N ☐ , E ☐ , S ☐ , W ☐

Remarks: