

# Ecological Aspects of Lightning in Forests

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## INTRODUCTION

LIGHTNING is part of the physical environment of many forest ecosystems throughout the world. Its ubiquity is reflected in Brooks' (1925) estimate that the earth experiences some 44,000 thunderstorms per day and that about 1,800 storms are in progress at any given moment.

According to the U.S. Department of Commerce (1966) these storms produce some 8 million cloud-to-ground discharges each day. If evenly distributed over the earth, about one-half million of them would strike in the world's 4,100 million hectares of forested lands. Recent satellite data collected by Vorpahl et al. (1970) and by Sparrow and Ney (1971) suggest that Brooks' early estimates may have been high and that 10 times as many night storms occur over land as over sea. In any case, lightning strikes thousands of trees around the world each day (Fig. 1).

The purpose of this paper is to indicate that lightning has a pervading influence on all trophic levels in the biological community, and that it affects the physical environment as well.

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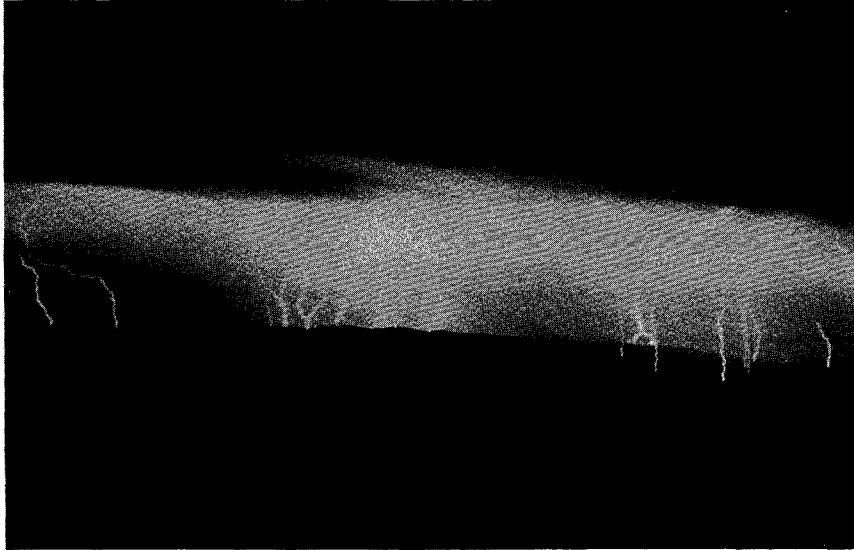


FIG. 1. Time exposure from a forest fire lookout shows several minutes of lightning activity in a northern Rocky Mountain forest. (Photograph courtesy David L. Dillon).

### LIGHTNING AS A CHANGE AGENT

It is a basic ecological premise that plant communities are dynamic, that they are characterized by constant change (Cooper 1926; Oosting 1956; Vogl 1970; Ahlgren 1973). Plant communities thrive under, indeed require, such change. To the forces of change they owe a healthy diversity of species, age, and form, much of the necessary recycling of nutrients, and their ability to perpetuate themselves. Lightning, in its role as a predator of both old and decadent members, as a precursor of insects, wind, and diseases, as a fixer of atmospheric nitrogen, and as an igniter of wildland fuels, has acted over evolutionary periods to *insure* that change occurs in plant communities.

### LIGHTNING AS A PREDATOR

Lightning acts as a predator of trees and other primary producers

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in forest communities through direct structural and physiological effects upon both individual trees and small groups. It removes the old and decadent members in a closed stand, thus creating openings that may result in species heterogeneity and changes in microclimate and wildlife habitat. Also, it sometimes strikes young and vigorous trees and is well known for attrition of single trees growing in the open.

### STRUCTURAL EFFECTS

The most frequent signs of lightning in forest communities are the structural effects on individual trees. These effects range from minimal disruption (Orville 1968) to virtual destruction of the tree (Fig. 2). Intermediate effects on the trunk include removal of a few outer bark flakes, one or more spiral bark furrows, ejection of wood slabs, and splitting and cross-sectional severing of the trunk.

On coniferous and rough-barked deciduous trees the most common structural effect is a uniform furrow 5 to 25 cm. wide that spirals along the trunk exposing only the outermost layers of sapwood in its path (Fig. 3). Such furrows frequently exhibit one or more narrow ridges or strips of crushed inner-bark tissue along the axis of the furrow (Fig. 4) (Taylor 1965). On smooth-barked species, lightning usually tears the bark away in large, irregular patches or strips (Vanderlinden 1907).

Structural effects are most obvious on the trunk, but all parts of a tree are vulnerable to lightning; lateral roots may be severed, limbs scarred, and branchlets and needles may be ruptured by flying bark and wood debris. In the latter case, needle clusters to a radius of 3 m. from a struck tree bole may be pierced or sheared off by a dense shower of finely divided bark and wood particles forcefully ejected from the bole by the discharge (Figs. 5 and 6). Since first observing this lightning effect in 1967 (Taylor 1969a), I have found evidence of it on some 60 newly struck conifers in the western and southeastern United States. In later sections we will discuss implications for insects and forest fire suggested by this shower of bark, wood, and needle debris.

From the literature and from myriad observations there can be

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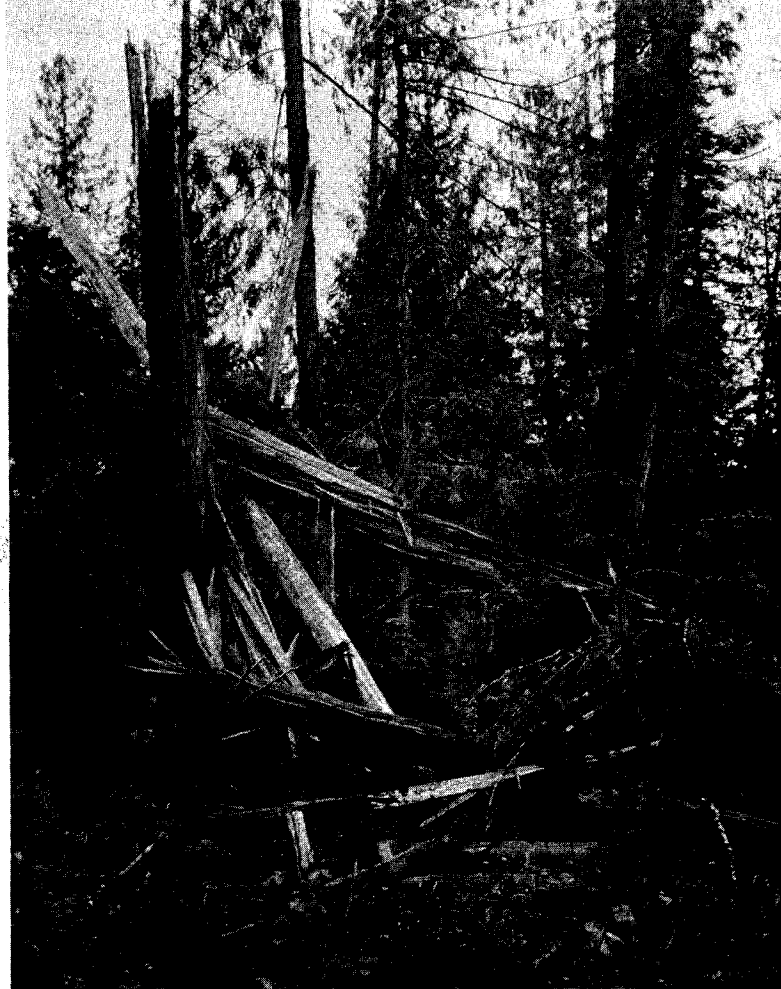


FIG. 2. Lightning virtually demolished this 37-m. tall grand fir in northern Idaho, 1969. (USDA Forest Service photograph by author.)

little doubt that the discharge typically parallels the grain of the tree, and that it does so because the alinement (often spiral) of the structural elements of the inner bark and wood that make up the grain provide the best electrically conductive paths in the tree. But

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FIG. 3. Two mature ponderosa pines in northern Arizona show typical lightning effects. Three bark-depth furrows on tree in foreground parallel the inner bark and outer wood grain. (USDA Forest Service photograph.)

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FIG. 4. Closeup of one lightning-caused furrow in Figure 3. Note dark strip of crushed inner bark tissue along furrow's central axis. (USDA Forest Service photograph.)

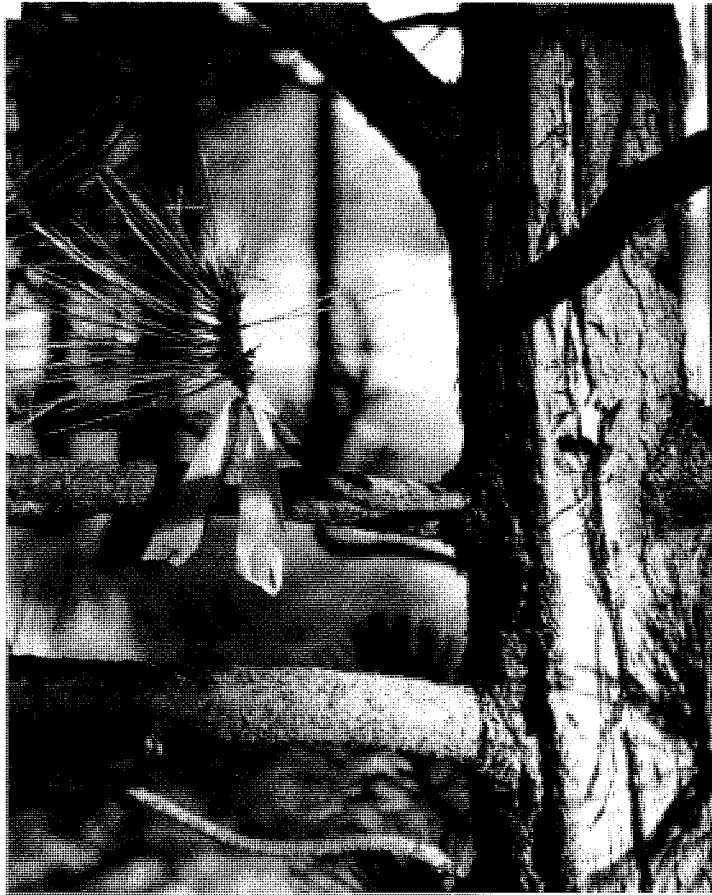


FIG. 5. Ponderosa pine needle cluster decimated by finely divided bark particles forcefully ejected from bole (note furrow) by lightning discharge. (USDA Forest Service photograph by author.)

we know little about how a specific path is selected and established along the tree bole. We can probably reject out-of-hand, for structurally damaged coniferous trees at least, the oft-cited hypothesis that the discharge initially selects a path along the outer, rain-wetted bark surface. If this were true the resultant structural effects would then essentially lie along a straight line down the tree without regard to the grain alignment inside the tree, and this clearly is not the case.

One possible explanation for path selection is that when lightning

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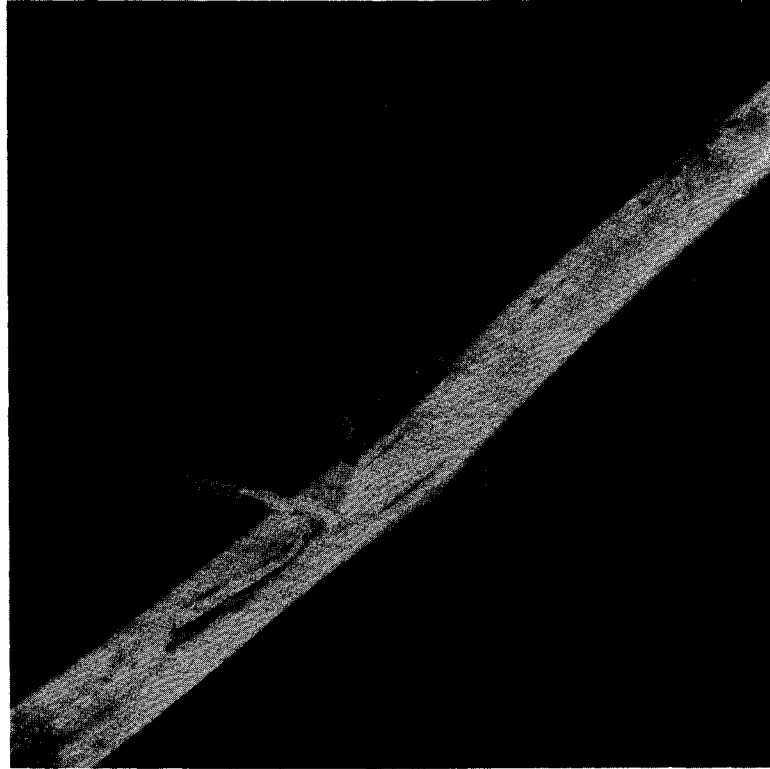


FIG. 6. Particle of outer bark embedded in a needle from damaged cluster shown in Figure 5. (USDA Forest Service photograph by the author.)

strikes a tree, the current is first discharged along the grain through the cambial region of the trunk. As the resulting potential gradient increases along the current path, it quickly reaches a value greater than that of air outside the tree, and surface flashover occurs.<sup>1</sup> The resulting effects may thus be due to the shockwave set up by the discharge at the outer surface of the trunk.<sup>2</sup>

<sup>1</sup> R. H. Golde. Personal communication, July 1972.

<sup>2</sup> Guy G. Goyer. On the mechanism of bark damage and forest fire inception by lightning discharges. Unpublished report on file at National Center for Atmospheric Research, Boulder, Colorado, 9 p., typed, 1966.



## PHYSIOLOGICAL EFFECTS

Some trees die within a few weeks or months after being struck by lightning, occasionally showing no visible mechanical injury on the bole (Stone 1914); others survive several disruptive discharges over the years (Taylor 1969b). However, most trees are not killed outright and eventually recover from effects of the discharge unless subsequently affected by other injurious agents. This is so because, in paralleling the grain, the discharge usually disrupts less than one-fourth of the tree's circumference. Thus, contrary to Hawley and Stickel (1948), even when the lightning furrow spirals around the trunk the tree is not usually girdled, and metabolic processes may continue in adjacent undamaged wood and bark tissue (Fig. 3).

This is not to say that trees are physiologically unaffected by lightning discharges. Although detailed effects are virtually unknown, Hodges and Pickard (1971) have shown in Louisiana that lightning strikes on 17 loblolly pines (*Pinus taeda* L.) markedly reduced oleoresin exudation pressure, oleoresin flow, and relative water content of inner-bark tissue. The injuries further resulted in a decrease in sucrose and an increase in reducing sugar content of the inner bark. Anderson and Anderson (1968) reported similar water-relation disturbances in a single loblolly pine struck by lightning in North Carolina. They proposed that lightning caused extensive physiological (unseen) damage to the tree's root system, which caused loss of hydrostatic pressure from the top progressively down the bole.

The physiological lightning effects *least* understood are those attending mortality of tree groups. In these events, a typical pattern results where lightning either kills or injures trees in compact, often circular groups (Fig. 7); the number of trees affected may range from a few to a hundred or more. There is usually a focal point near the center of the group where one or two trees show structural effects and where trees of all sizes and even low shrubs may have been killed. Mortality may decrease toward the periphery of the group where only some higher inner-facing branches of the taller trees die (Anderson 1964).

Tree-group mortality of this type has seldom been reported in the United States and Canada (however, see Boyce 1961; Baxter

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FIG. 7. Group of Monterey pines killed by lightning in Ovens Plantation, Victoria, Australia. (Photograph courtesy G. Minko and Forests Commission, Victoria.)

1943) but has been commonly observed throughout Europe, in England, Scotland, Australia, New Guinea, and Malaysia (Hauberg 1960; Peace 1940; Murray 1958; Minko 1966; Shaw and van Velsen 1969; Brunig 1964, respectively). From England, the British Forestry Commission (1970) reported that lightning killed some 250 pole-stage scots pines (*Pinus sylvestris* L.) in a group; and in Victoria, Australia, during the period 1959–1969 Minko<sup>3</sup> mapped 24 group kills, each containing 11 or more Monterey pines (*Pinus radiata* D. Don) on the 1,620-ha. Ovens Plantation. During the same period he charted 77 additional sites on the Plantation where lightning had killed from 1 to 10 trees per discharge.

<sup>3</sup> Personal communication, 1970.

Neither the mechanism of lightning-caused tree-group mortality nor its apparent infrequency in North America is well understood. Herrmann (1942), Hauberg (1960), and Bosshard and Meier (1969) propose that the discharge affects root systems of trees surrounding the initially struck tree; however, Murray (1958) and others suggest that lightning may strike a few trees in a group, travel along their trunks, and cross to neighboring trunks by way of their branches. Finally, Minko (1966) has suggested the possibility of a discharge having a horizontal component that flashes through the forest canopy. In view of the increasing documentation of widespread intraspecific root grafting by more than 150 species of trees (Graham and Bormann 1966; Wood and Bachelard 1970; Schultz 1972), a hypothesis implicating root grafting in lightning-associated group mortality is in order.

Regarding the apparent scarcity of tree-group killing by lightning in American forests, Komarek (1964) suggested that it occurs frequently but is often masked by and attributed to other agencies that affect groups, as discussed below.

### LIGHTNING AS A PRECURSOR

We have seen that lightning acts directly upon many individuals and small groups of trees every day, but of greater biological significance is that the direct structural and physiological effects of lightning are precursory to other physical events in the environment and to important biological activities by consumers and decomposers.

#### SCOLYTID BEETLE ATTACK

In 1966, while flying low over a coniferous forest of western Montana we observed a lone mature ponderosa pine (*Pinus ponderosa* Laws.) surrounded by dying pine saplings. Investigation revealed (Schmitz and Taylor 1969) that this mature tree had been struck by lightning, and along with 73 of the 96 younger trees within 25 m. radius had been subsequently attacked by pine engraver beetles *Ips pini* (Say) (Coleoptera: Scolytidae). Such lightning-associated tree-group events, seldom reported in the northern Rocky

Mountains, are common in pine forests throughout the southern half of the United States.

Forest entomologists are aware that individual conifers damaged either by lightning or other injurious agencies attract several genera of scolytids (Hopkins 1909; St. George 1930; Miller and Keen 1960; Rudinsky 1966; and Johnson 1966). Sharpening this awareness, Anderson and Anderson (1968) proposed that pioneer flights of *Ips* bark beetles are attracted to lightning-struck southern pines by volatile oleoresin fractions released from ruptured bark and wood tissue. Then, as was apparently true in the case described above, attacks by a few pioneer beetles on a single lightning-struck tree may trigger mass attacks on the struck tree and its neighbors (Thatcher 1960; McMullen and Atkins 1962). Providing more recent evidence of this, Hodges and Pickard (1971) have reported that individual lightning-struck pines were epicenters for 31 percent of the 2,100 tree-group beetle infestations recorded in a 3-year period on one large ownership in Louisiana.

It is generally assumed that the bark beetles are solely responsible for the tree-group mortality in such cases. But the common occurrence of the type of group killing described in the previous section, where lightning-struck tree groups die in other parts of the world in apparent absence of insect attack, prompted Komarek (1964) and Schmitz and Taylor (1969) to suggest that lightning does unseen damage to tree groups in North America as well, making them more susceptible to beetle attack.

In the section on structural effects we described the lightning-caused shower of finely divided bark, wood, and needle particles. This debris may be deposited in bark crevices and on foliage of neighboring trees to a radius of 50 m. or more from the struck tree, and in the frequent case where the lightning furrow spirals around the tree bole, debris is scattered full circle (Fig. 3). Although this phenomenon is virtually unknown to entomologists, it may be important in understanding host selection by scolytid beetles because, as noted above, volatile oleoresin fractions released from the disrupted tissues elicit an olfactory response by pioneer beetles. The debris shower, in effect, places a multitude of minute, short-term oleoresin-

releasing sources on and around the struck tree and its neighbors. An especially dense shower might enhance the probability of discovery and attack by pioneer beetles in an otherwise marginal olfactory-search situation.

#### WIND EFFECTS

It is obvious that trees mechanically weakened by lightning may be especially susceptible to structural failure in high winds. Although probably overrated, it is a widely held view that lightning usually strikes either lone trees or the older, taller trees in a stand (Thompson 1946; but see Taylor 1964). To the extent that this is true, lightning may be considered a precursor of windthrow and wind breakage, because either lone or taller trees that project well above the forest canopy are most subject to the vagaries of wind.

More important, in terms of lightning-associated wind effects on the biological community, are the openings created by lightning-caused group mortality in some forests of the world. In the *Shorea albida* forests of Sarawak for example, where such lightning gaps are so numerous as to require consideration in management planning and forest inventories, Brunig (1964) showed that they frequently produce 30- to 100-m.-long, narrow swaths of windthrown trees. In Australia also, lightning-killed groups of Monterey pine become epicenters for windthrow that may extend into the surrounding stand (Minko 1966). Thus, as is true for lightning and certain forest insects, lightning acts as a precursor to winds that create open spaces and also cull older, mature trees in a stand. The same principle applies for lightning and forest diseases.

#### MICRO-ORGANISM INVASION

Mechanical injuries on living trees, especially those extending into the heartwood, are recognized by forest pathologists and mycologists as important courts of entry for many disease organisms. Given the likelihood that several millions of trees are struck by lightning around the world yearly, it seems reasonable to suggest that lightning is an important precursor of this class of consumers (Fig. 8). While scattered references in the world forestry literature do cite lightning as



FIG. 8. Evidence of disease resulting from a lightning wound in a sugar maple tree. (Photograph courtesy Peter H. Kourtz and Canadian Department of Forestry and Rural Development.)

a disease precursor (Boyce 1920, 1961; Wagener and Davidson 1954; Peace 1962; Mook 1966; Kimmey 1964; Kourtz 1967; Bosshard and Meier 1969; Hinds 1971), few regard it as an important one in terms of frequency. This apparent anomaly is probably due to a combination of the following: (1) Many, perhaps most, lightning wounds are superficial and may not offer a substrate conducive to pathogen survival (Boyce 1920; (2) decay caused by invading micro-organisms may ultimately mask the original lightning effects so that they go

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unrecognized; and (3) other disease precursors (e.g., wind, fire) are so prevalent that they far outweigh lightning in importance.

In support of (2) above, Sharples (1933) and Dwyer (1936) showed that lightning was responsible for the mortality of Malayan coconut palm (*Cocos nucifera*) that for years had been attributed to bud rot disease, and Weir (1928) reported that the so-called dieback disease of rubber trees (*Hevea brasiliensis*) in Malaya was actually a lightning effect masked by subsequent disease organisms.

Recently Vogl (1968) suggested that crown rot of the California fan palm (*Washingtonia filifera*) is preceded by lightning injury to its terminal buds; and from Switzerland, Bosshard and Meier (1969) reported that lightning is a precursor of root rot (*Armillaria mellea*) which is widespread in conifer groups. Currently, Steenbergh (1972) has shown that the well known bacterial necrosis disease (*Erwinia carnegiana*) of mature saguaro cactus (*Cereus giganteus* Engelm.) in the southwestern United States is in reality *not* a killer of healthy saguaros but a rapid natural decomposition process following death or critical injury caused by lightning and other climatic phenomena.

These examples provide ample evidence that lightning-effects/disease-associations have gone unnoticed, and they suggest that lightning may be more important in this regard than is generally recognized.

#### NUTRIENT CYCLING

To the extent that the effects of lightning result in fire or in mortality, the discharge has an indirect effect on nutrient cycling in the forest community. But lightning plays a more direct role by fixing atmospheric nitrogen.

All lightning discharges cause some nitrogen in the atmosphere to unite with oxygen to form nitrogen oxides. These oxides combine with atmospheric moisture to form dilute nitrous and nitric acids which are brought to earth by rain. The acids act on soil minerals, and soluble nitrogen-containing salts are formed in soil water. Delwiche (1970) estimates that of a total of 92 million tons of nitrogen fixed each year, some 8 percent is atmospheric, about 30 percent industrial, and the remainder biological. Uman (1971) estimates that

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lightning fixes less than 2 million tons of Delwiche's total atmospheric estimate, and that the remainder may be fixed through other atmospheric processes.

### LIGHTNING AS AN IGNITION SOURCE

#### IMPORTANCE

I estimate (from incomplete statistics) that lightning causes about 50,000 wildland fires per year worldwide. Clearly, this represents less than 1 percent of the estimated 182 million cloud-to-ground discharges occurring in the forests and grasslands of the world each year, and as expected, such fires are not evenly distributed (Taylor 1971). While they occur at least occasionally in most parts of the world, their frequency and biological impact are probably greatest in western North America.

Of the approximate total of 1.1 million wildland fires that occurred due to *all* causes in the United States during the years 1961–70 (USDA Forest Service, 1961–70), some 100,000 were caused by lightning. The map in Figure 9 shows the total number of fires during this period and the number and percent of them caused by lightning for five groups of States.

About 83 percent of all lightning fires in the United States during the period occurred in the forest and grasslands of the Rocky Mountain and Pacific groups, collectively.<sup>4</sup> There, lightning is the greatest cause of wildland fires. The fuel and climatic conditions are especially conducive to ignition by lightning, and a single lightning storm may start tens of small fires in minutes over many square kilometers (Fuquay 1962).

#### IGNITION MECHANISMS: A HYPOTHESIS

Based upon earlier work by G. G. Goyer<sup>2</sup> and upon our subsequent field observations and tests in western Montana, the author and C. W. Schmid, Jr., offer the following hypothesis for a mechanism of forest fuel ignition by lightning:

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<sup>4</sup> The data show that Hawaii recorded only two lightning fires, 1961–70. But see Vogl (1969) for a critical examination of lightning fire occurrences in Hawaii.



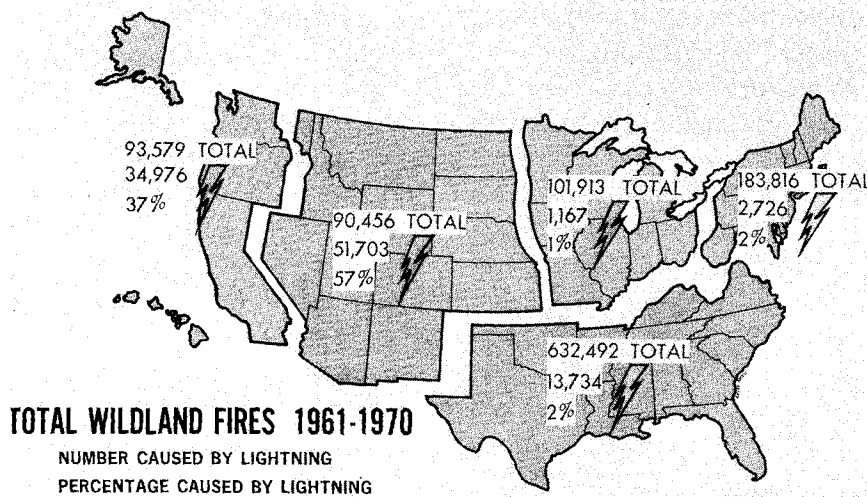


FIG. 9. Wildland fire occurrence, 1961-70, by groups of States. Upper value in each group shows total number of wildland fires for the period, all causes considered, on all protected Federal, State, and private lands. Middle value is the number caused by lightning, and lower value is percent of total (upper value) caused by lightning. (Data from USDA Forest Service 1961-70.)

A lightning discharge striking and rupturing a live conifer produces and ignites a mixture of volatile extractives and finely divided bark, wood, and needle particles (<3 mm. dia.) to an intense, short-lived (<1 sec.) ball or column of fire which in turn ignites flash fuels in the tree crown or on the forest floor.

We'll return to this hypothesis, its biological implications, and the results of preliminary trials conducted to exclude it after some remarks on lightning-caused ignition mechanisms in general.

Except for occasional efforts to isolate the long-continuing current discharge thought most likely to cause fire (McEachron and Hagen-guth 1942; Norinder et al. 1958; Loeb 1966; Fuquay et al. 1972), ignition mechanisms have held only peripheral interest for most workers in the lightning research field. Most writers of general texts

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on lightning have given perfunctory attention to the problem (but see Uman 1971). usually alluding to Joule heating (resulting from conduction currents within forest fuels) as *the* mechanism of ignition.

There is some doubt as to the efficacy of internal Joule heating in causing forest fires. C. W. Schmid<sup>5</sup> suggests, on theoretical grounds, that the initial conductive paths within a forest fuel element should give way during the discharge process to an arc channel, or flashover, *outside* the conducting member, thus precluding any appreciable Joule heating within the member.

Goyer<sup>2</sup> reported an unexpected 3-m.-diameter fireball attending primacord (explosive cord with 50-grain PETN core) detonation tests on three pine tree boles in South Dakota. Goyer reasoned that the *expected* (free air) < 1-m.-diameter luminous combustion column from the detonated primacord was fed by bark scales and particles, dry needles, and small branches shaken loose by the shock-wave, and he proposed that lightning might create a similar fireball that ultimately could ignite fuels on the forest floor.

Goyer's unexpected fireball brought to mind an often-reported but unexplained phenomenon occurring at the ground terminals of lightning discharges, and known colloquially to the forest fire lookout in the West as "flareup." Although observer descriptions vary considerably, in general the visible phenomenon may be characterized as follows:

As viewed from 1- to 5-km. distance, it begins while the discharge channel is visible, and it has a duration of from several tens of msec. to several seconds after the channel is no longer visible. Its apparent shape ranges from that of an inverted cone to a sphere, having a maximum apparent diameter approximating the crown diameters of nearby individual trees. It does not appear to move about; it is often red or orange in color, and sometimes gives an observer the impression that the entire crown of a tree at the base of the channel is momentarily aflame. Indeed, sometimes the crown foliage of the struck tree exhibiting a flareup *is* ignited and the fire spreads to other

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<sup>5</sup> C. W. Schmid, Jr. Mechanisms of forest fuel ignition by lightning. Unpublished report on file at Northern Forest Fire Laboratory, Missoula, Montana, 43 p. typed, 1969.

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fuels. At other times the flareup is followed by ignition in ground fuels at the base of a struck tree, but often the flareup is not followed by sustained combustion.

The lightning-struck ponderosa pine and its decimated needle cluster shown in Figure 5 were examined by Schmid and the author in 1967. Microscopic examination of the needles led to the embedded bark particles (Fig. 6) and ultimately to the finely divided bark, wood, and needle debris (< 3-mm. dia.) deposited on freshly ejected wood slivers from the struck tree (Fig. 10). No forest fire occurred at this site, but several regions of the deposited particles on some slivers were heavily charred; others showed no char.

During the ensuing year I examined some 40 newly-struck conifers for evidence of the fine-particle debris and found it present in varying amounts on all. Three of the trees were southern pines in Louisiana

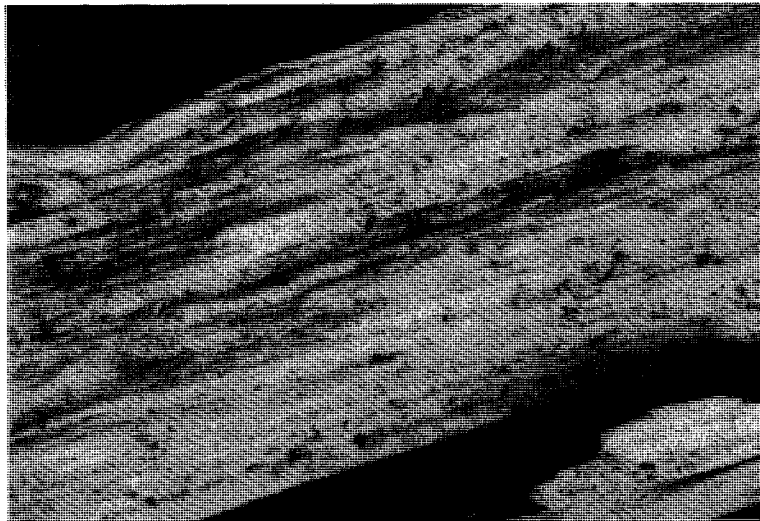


FIG. 10. Finely divided bark, wood, and needle debris collected on surfaces of wood sliver ejected by lightning out through the "debris shower" from a ponderosa pine in western Montana. Particles range from <0.05 mm. to about 3 mm. diameter. (USDA Forest Service photograph by author.)

and Georgia; the rest were among five species of conifers in western Montana and northern Idaho.

The wood, bark, and needle tissue of woody plants contain ether extractives composed of many compounds, including fats, waxes, oils, and terpene-laden oleoresins. Philpot and Mutch (1971) point out that these extractives are related to the total energy content of plants and are important in combustion chemistry because of their high energy content, their ready availability on exposed plant surfaces, and for some, a very low fuel/air ratio. The Chemical Rubber Publ. Co. (1957) lists turpentine, a natural compound of  $\alpha$  and  $\beta$  pinene terpenes, as having a lower limit of flammability (gas in air) of 0.80. There can be little doubt that the shower of bark, wood, and needle debris described above would quickly release a considerable volume of such flammable extractives to the air.

With these things in mind—doubt as to the efficacy of Joule heating, the flareup phenomenon, Goyer's unexpected fireballs, and our strong evidence of charred debris shower particles and their attending volatiles—Schmid and I determined to repeat and refine Goyer's tests. We did so in 1969, firing 2- to 7-m.-length strands of detonating cord attached to trunks of 13 live trees (one Douglas-fir and 12 ponderosa pines) (Fig. 11). We fired a total of 31 shots; 6 in free air, three against a newly debarked trunk section, 8 against wetted trunks, 14 on dry trunks. The *dry-bole* shots all produced fireballs having maximum diameters (photo image-width measurements normal to tree bole axis) between 1.6 and 4.2 m., and durations (film frame counts) between 250 and 880 msec. (Fig. 12). The fireballs settled to the ground and caused sustained combustion in grass and forest floor litter. The shots against artificially *wetted boles* and the debarked trunk section produced diminished detonation columns similar to those in free air (<1 m. dia. and  $\sim$ 30 msec. duration) and no subsequent ignition of ground fuels occurred.

All of the shots against fully barked boles produced fine-particle debris showers similar in particle shape, size distribution and appearance (at  $\times 10$ ) to those produced by lightning. Microscopic examination of bark particles captured on adhesive specimen plates near the trees (Fig. 12) showed no obvious differences between wet



FIG. 11. Live ponderosa pine wired with three 3.6-m.-length strands of 50-grain detonating cord, parallel to tree's grain and against dry outer bark surface, August 1969. (USDA Forest Service photograph by author.)

and dry shots in bark particle shape, size distribution, or numbers per unit area. Those particles captured from dry-bole shots were virtually all charred on their edges and surfaces, while only 4 to 10 percent of those from the wet-bole shots showed char.

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FIG. 12. Same tree as Figure 11 at time of maximum fireball diameter (horizontal measurement) about 150 msec. after detonation. Fireball settled rapidly to ground, causing ignition and sustained flaming combustion in grass and forest floor litter. Horizontal white rectangles that may be seen in foreground are adhesive-coated specimen cards for collecting debris samples. (USDA Forest Service photograph by C. W. Schmid, Jr.)

We suggest that the ignition hypothesis stated above, embodying Goyer's basic proposal but modified by our isolation of the ruptured needles, the minute debris shower particles, and the accompanying release of flammable extractives, is worth further study. Furthermore, the debris-raising and volatile-releasing features suggest an extension of the hypothesis to account for inception of some lightning-caused fires in open grasslands and in decayed logs on the forest floor.

*Biological Implications.*—If the proposed “debris shower” mechanism does operate in nature, our observations suggest that fireball genesis and development (in the case of live trees) are controlled largely by bark structure, extractive content and type, and bark

wettability, and by moisture content of the bark and surrounding air at time of discharge. This, if true, would closely link *lightning fire initiation* and *species characteristics*, and might further explain consistent differences in fire occurrence between regions having so-called "dry" lightning storms and those having rain-producing lightning storms.

#### FIRE EFFECTS

The annual cost of controlling lightning-caused fires in the United States is estimated by Barrows (1971) to approach \$100 million, about one-third of the nation's total annual fire control cost.

Most wildland fires, whether caused by man or by lightning, do not become conflagrations. Of the 63,195 lightning fires recorded on all National Forest lands in the United States during the years 1961-70, fully 97 percent were controlled at 4 ha. or less. In view of the high cost of suppression, and in view of emerging fire ecology literature that calls for greater understanding of the natural role of fire (Weaver and Biswell 1969; Kilgore 1970, 1972; Komarek 1968; Mutch 1970; Vogl 1973; Ahlgren 1973), it would be instructive to know how many of those thousands of small fires would have extinguished naturally at 4 ha. or less had they been allowed to burn.

We do know that most American forests have experienced fire for several thousands of years (Wellner 1970; Heinselman 1970). It is likely that most were of the order of a few hectares in size at natural extinguishment and only a small proportion became conflagrations. Heinselman (1970, p. 30) aptly states:

The primeval conifer forests of northern North America and their associated broadleaf elements were mostly fire-dependent ecosystems . . . [that is] fire was the key environmental factor that initiated new successions, controlled the species composition and age structure of the forests, and produced the vegetational patterns upon which the animal components of the ecosystem also depended. . . . Fire was the great reaper that periodically eliminated or opened up old forest stands, making way for new generations of trees. The primeval landscape was a vast mosaic of stands in various age classes and successional stages following fire, interspersed with recently burned areas.

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Hendrickson (1971, p. 83), speaking of fire in the present tense, reminds us that fire “. . . is a resource that structures the kinds and numbers of species present just as does the water resource, the climate and the soil.” To this we can add that wildland fire often exposes mineral soil and thereby prepares seedbeds for new members. It promotes the recycling (and some loss) of minerals through the burning of nutrient-laden organic matter (Behan 1970), and sometimes through stimulation of early-succession, nitrogen-giving plants (Wollum and Youngberg 1964). Also, wildland fire may produce the following: erosion in unstable soils; either the destruction of habitat or the development of increased or varied wildlife habitat (Ward 1968; Bock and Lynch 1970); creation of epicenters for the spread of insects, disease, windthrow, and future fires. Indeed, fire embraces all environmental parameters in most forests of North America.

A still fuller understanding of the natural role of fire is critical if we are to manage wildlands in harmony with nature, but it is already clear that, in some ways, fire is beneficial and necessary to many plant and animal communities.

#### LIGHTNING IN PERSPECTIVE

We have seen that although the influences of lightning in forest communities may sometimes be obvious, more often they are subtle and go virtually unnoticed. There is an even more subtle level of lightning influences that we have scarcely begun to understand: the possible photochemical and acoustical effects of the flash and its shockwave on plant and animal life; the direct electrical effects on plant root systems, forest wildlife, soil and its micro-organisms; the roles of thunderstorm updrafts and downdrafts in insect, spore, seed dispersal; long-term genetic response to fire, and others. Given the ubiquity of lightning, its many influences are probably more common and biologically more important than have been generally recognized.

It is indicative of our lack of perspective and understanding of nature that people consider most of the lightning effects discussed



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in this paper to be harmful to the forest and deleterious to man's needs and interests. It is true that insect-infested stands and structurally damaged and diseased trees represent resource and esthetic losses. It is undeniable that a few lightning fires become holocausts. These effects unquestionably justify research effort toward their amelioration and control. But the greater challenge facing man is to gain and diligently apply new biological insight concerning the roles of lightning and fire in plant and animal communities, to couple this knowledge with technological capabilities to prevent disasters associated with lightning, and yet allow this change agent to pursue, to considerable extent, its natural course.

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