Lightning and Lightning Fires as Ecological Forces

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THE ecological aspects of lightning, and lightning fires have a profound impact on living organisms themselves as well as upon the environment in which each lives. They should be considered as a very definite part of that environment. They operate in accordance with basic natural laws and man's consideration and use of them must be within the boundries of these laws. This paper is an attempt to bring about a better ecological understanding of lightning and lightning fires, as they concern living organisms and their habitat. The comprehension of these forces is difficult because of their great variability: "Life is a condition difficult to define because it does not denote one constant state in a body to which it pertains, but refers to a series of changes continually occurring." (Smee, 1849).

Life is a tenuous thread that reaches back to its own beginning and yet at the same time holds promise for the future; truly, every living thing is related to every other living thing that was or will be. This thread—this "fragile breath of life"—compelled by natural forces to live within very narrow limits, adapts itself to great changes in its environment. This is attested to by its very existence in multitudinous forms during its long history on an ever changing earth. "Unlike a stone, whose passive existence is simply the result of its own hardness, and of the fact that few natural forces tend to change it, living organisms, including man, must actively seek certain stable conditions under which their continued existence is possible." (Vossler and Uhr, 1961). Life's strength, perhaps, lies in the fact that no two living things have ever been, or ever will be, *exactly alike* for exactness is not a function of life; "the balance of life . . . is never complete."

The individual living organism has birth, growth, and death, changing all the while from moment to moment. However, as an entity it has continuity through reproduction, changing ever so slightly, generation by generation, unless some factor in the environment causes extinction. Life does not exist alone; we have not only many diverse forms of living things, but also various and complex associations or communities of plants and animals. We cannot define with mathematical accuracy the various stages from birth to death, the continuing life stream, or the associations of many different living and non-living things. We can, however, ascertain regular and re-occurring patterns in life's behavior and the relationship of living things, one with another, as well as with the environment in which they live. One such example, greatly influenced by lightning and fire, is *succession.*

Associations of living things succeed each other in much the same way as does the individual. They have a birth, adolescence, maturity and death. These patterns of succession in nature have various succeeding steps which we call pioneer (birth-juvenile), seral (growth-young), and climax (maturity-death). Whittaker (1952) gives a very thorough and excellent summary of the many theories or ideas relative to plant succession. Although this paper concerns only plants, the ideas expressed therein can be extended to include animals as well. He points out also the inexactness and difficulties in such studies concerned with living organisms: "Vegetation presents a field of phenomena notably lacking in fixed points of reference, lines of division, invariable rules, and easy definition. The spatial pattern of natural communities is so complex that it is beyond a reasonable possibility to achieve understanding in full detail. Nevertheless, we can recognize repeating patterns, trends, and methods of behavior in plant and animal groups or associations."

We can predict that under a prerequisite set of conditions certain successional stages will ensure, but never in "full detail." We can comprehend the action of ecological forces upon living things if we understand that we are concerned with living things and that exactness is not a function of life; life will not reduce to a mathmatical formula.

Patterns of change which reoccur, vary and evolve by natural selection are formed by the complexities of the birth, death, and re-birth of many living organisms with many different and transient life stages. The diversity of living things and how they live within the boundaries of their individual environment is further compounded by the variations in climate, soils, and topography. Throughout all this, "All living things have two things in common: a) they all convert energy at a continuous finite rate and, b) they all have a finite life span." (Ruderfer, 1964). It is upon this kaleidoscope of life and its environment that lightning, and lightning fire, have their dramatic effect.

LIGHTNING AS AN ECOLOGICAL FORCE

The impact of lightning as a natural ecological force on living organisms and their environment has been of great interest to me for well over the past two decades, largely as an outgrowth of my studies in fire ecology. It has become apparent that lightning fires are only one illustration of the ecological effects of lightning and that lightning itself is only one example of a basic natural and ecologically important component of the universe; electricity. The development of this concept has been gradual and evolutionary and has resulted in several papers, Komarek (1962–1967). This discussion is an effort to bring together and review some of the ecological relationships of electricity to the living world and its environment. Lightning and lightning fires are the most obvious, more easily understood, and better documented aspects of this interesting field.

Lightning discharges bombard the earth daily and have done so throughout its history. Estimates have been made by many investigators as to the number of lightning strikes that occur. Brooks (1925) estimated that there were about 1800 thunderstorms in

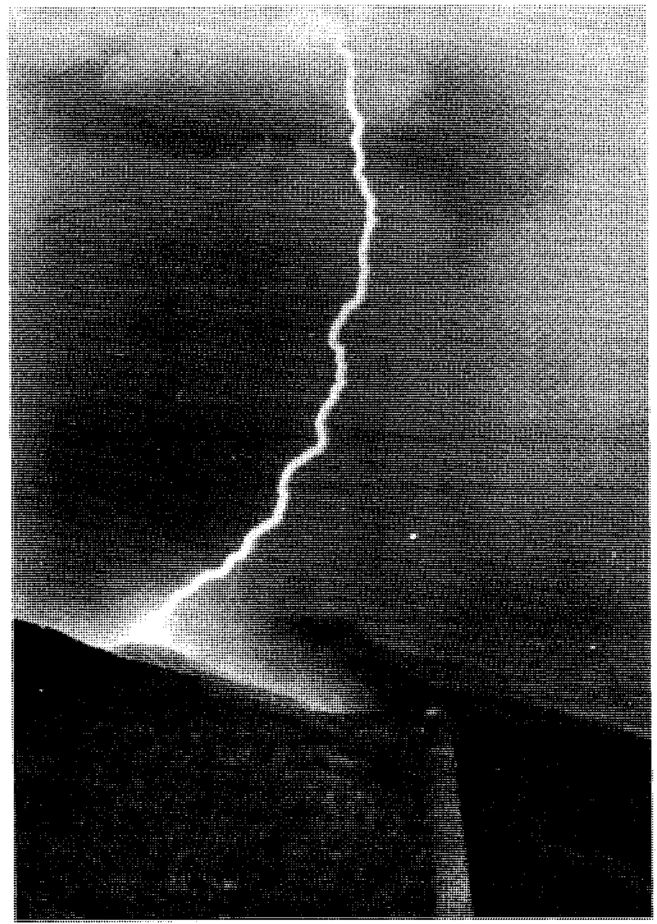

FIG. 1. Lightning strike on Tanque Verde Ridge, Saguaro National Monument, Arizona, August, 1967. (Photo by Harold T. Coss)

progress over the earth's surface at one time. McCann (1942) wrote that, "Each year about 16 million thunderstorms occur on the earth causing an average of about 50 lightning strokes to the earth each second, or a total of about two billion strokes a year . . ." and that if these were "equally distributed, about eight strokes a year would

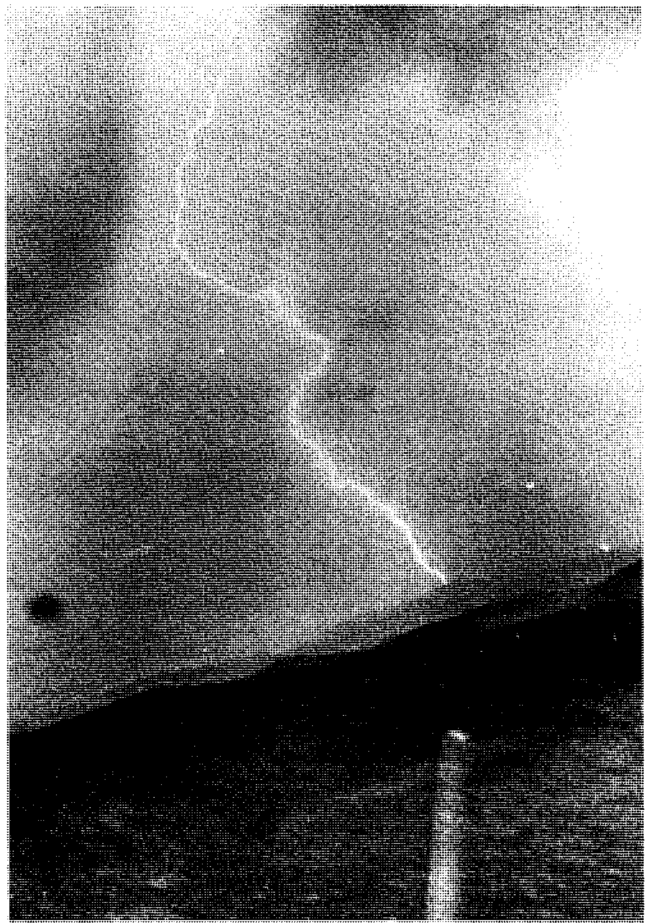

FIG. 2. Lightning strike on Tanque Verde Ridge, Saguaro National Monument, Arizona, August, 1967. About one minute after strike in Fig. 1 "in a real 'hot' storm" (Photo by Harold T. Coss)

strike each square mile of the earth's surface," Arnold (1964) stated that "during the next 20 minutes these storms will produce 60,000 cloud-to-ground lightning discharges." This is at the rate or 3,000 discharges per minute or 50 per second. Komarek (1964) reported that estimates of lightning strikes to the ground had been increased to

100 such strikes per second, 24 hours a day for 365 days a year. In 1966 he estimated 2,739 lightning thnderstorms passing over about 275,000 square miles of central United States in a 1 hour period at midnight. This represented only one frontal activity and these fronts sweep the North American continent on an average of once every 7 to 10 days in the summer. Davis (1967) registered 1,860 discharges on an electronic recorder with an effective range of only 10 miles as one small thunderstorm passed over his instrument. Similar electronic recorders operating as a net at strategic points over the continent in Australia (Anon. 1967) are regularly registering lightning strikes in the thousands.

The intensity of some of these lightning strikes has ranged well into hundreds of thousands of volts and a current as high as 340,000 amperes. The lightning flash we see represents many different strokes and as many as 47 have been counted in one such discharge. We now know also, that the discharges from the thunderstorms can move over areas, and that they can occur in clusters, groups, or in long streaks or pathways for considerable distances. Likewise, there can be many side streamers and these as well as the discharges themselves can be of various voltages and currents. Fuquay *et al.*, (1967) recorded and measured the characteristics of lightning discharges to the ground at Missoula, Montana and found differences in the length or continuity of the current.

Malan (personal discussion) has mentioned that the number of strikes from cloud-to-cloud and from cloud-to-ground or vice versa vary greatly and that some thunderstorms discharge mostly to the ground and others hardly at all. MacDonald (1960) has suggested that "thunderstorms replenish the earth's charge" and made charts that indicate this possibility. Battan (1964) pointed out that thunderstorms were vital in "keeping circulation of the atmosphere in proper balance" and that they "must be regarded as necessary parts of nature's plan." Komarek (1966) stated that "thunderstorms may be a very necessary part of the atmosphere to maintain the electrical stability of the earth's electrical potential." An unbelievable number of lightning strikes occur with great variability in the characteristics of the discharges themselves. Lightning is a very important component of our atmosphere.

LIGHTNING AS A FOREST PREDATOR

The impact of lightning discharges on forest ecology has been studied only by a few investigators but in several regions. Krauch (1930) pointed out that lightning was one of the major causes of mortality in western cut-over ponderosa pine forests. Pearson (1939) reported on the detailed studies of ponderosa pine mortality in several plots ranging in size from 168 to 320 acres and over a period of from 10 to 25 years. They contained both mature and cut over forests. In these studies the evident lightning mortality was between .7 to *1 percent per year*. He also pointed out that many of the trees that were listed as having died from insects, wind, etc., may have been injured by lightning without any obvious external evidence. Lightning damage was cumulative; some trees were repeatedly struck with little early mortality. Pearson and Wadsworth (1941) showed that 91.2 percent of the volume (board feet) in timber mortality in ponderosa was mainly due to three agents; wind, lightning and mistletoe. Wadsworth (1943) stated that, "Lightning accounts for about one-third of the total timber mortality in the ponderosa pine forests in northern Arizona, and in addition results in a considerable amount of defect which has not been measured. Of the trees struck some are killed instantly, some linger one or more years and succumb to bark beetles, and still others recover." Nelson (1958) concerning eastern hemlock wrote that "visible lightning scars were present on 25 per cent of the dead trees. However, the total percentage of lightning-killed trees is no doubt higher than 25 since trees are often killed without leaving a visible scar." Reynolds (1940) reported that in Arkansas lightning was responsible for about 70 percent, by volume, of the mortality in southern pines. From these studies it would appear that a lightning mortality in forest stands of 1 percent per year may even be a very conservative figure.

There are many indications that lightning may weaken trees without much if any, external obvious damage. One of these is the formation of "lightning rings."

> The cambium, being the line of least resistance, is particularly susceptible to electrical discharges, and the classical investigations

> of Martig (1897) have demonstrated the formation of abnormal tissue in trees showing no outward indications of injury. In the bark areas of hard tissue (*Blitspuren*) lighter in color than normal are developed . . . and in the wood lightning rings are formed that may extend entirely around the trunk circumferentially and for many feet vertically. These rings are formed in the annual growth rings, and in some conifers are commonly characterized by an abnormal number of resin ducts . . . (Boyce, 1948)

Several writers have mentioned the fact that ponderosa pine trees can at times be struck by lightning and not killed. A few instances have been noted of repeated strikes on the same tree. My wife and I, in an examination made of several hundred trees south of Flagstaff in 1966, found that about 30 percent of the trees had one or more strikes and were still in apparent good health. Several years earlier we had found about the same phenomena in Schultz's Pass in the San Franscisco Mountains of Arizona. Here in northern Florida and southern Georgia we have noted many trees that apparently recovered from lightning damage and healed over but not to the extent found in ponderosa forests in Arizona. Apparently, many times the lightning discharge will travel through the cambium and still not split the bark.

A characteristic of some electrical storms, to kill or injure trees in groups or clusters of up to an acre or more, has been reported by several investigators. Boyce (1948) wrote:

> Small, roughly circular groups of conifers, but not hardwoods, may be killed by a diffuse electrical discharge without the trees showing any outward visible wounds . . . This possibility may explain the small groups of dead trees which often occur in the mature Douglas fir forests of western Oregon and Washington, for which no definite cause has been found. The tops of conifers may be killed the same way without any outward signs of lightning being apparent.

However, it would appear from the following personal observations that hardwoods even when mixed or surrounded by conifers can be affected by such groups of electrical discharges as well. In June 1966, an electrical storm passed over our house (Birdsong Plantation, Grady County, Georgia) which has one very large pecan tree on the west side of the building and 4 acres of smaller but mature pecans adjoining the east side. The house and grove area is surrounded by mature pine forests of loblolly, longleaf, slash and shortleaf pines interspersed with groups of hardwoods. There are likewise several pine trees in the yard area, some of these are of original growth longleaf pine which are much taller than any of the pecans. As this storm passed by, electrical discharges struck five of the pecan trees and did not apparently strike or affect any other trees nearby. In four of these, including the large pecan (which had been braced with tree cables) the lightning damage was in the form of narrow streaks where bark had been torn loose. This damage was only on the upper sides of the main branches in all five trees and no sign of where the charge came down the tree or went into the ground could be found. In the other pecan only the top leaders and topmost branches were affected. These were partially scorched and the branches looked as if they had been twisted severely by some external force. Two years later all five trees apparently have recovered. The distance between the farthest struck trees was about 500 feet. At nearly the same time this storm struck the WCTV tower as well as several large pine trees at Tall Timbers Research Station some 3 miles away.

In July 1966, an electrical discharge hit a small roughly circular area about 300 feet across on Birdsong Plantation about 2,000 feet from the above. In this instance three loblolly pine trees and two white oak trees were affected. Of these, two were large loblolly pines about 32 inches dbh and another, a large white oak about 37 inches dbh. The other trees were small saplings about 10 inches dbh. In this example two streaks were torn out of the oak. Some of the strips that had been torn out were up to 8 feet long, 2 inches wide and about 2½ inches thick. One narrow streak was observed on one of the large loblolly pines to the south of this oak. The other large pine tree some 50 feet west of the oak showed no signs of damage. However, shortly thereafter this tree's foliage turned yellow and the tree died some 6 months later. Two years afterwards, when the bark had fallen off the tree, a faint spiral mark could be seen from the ground level to way up into the tree. Now the oak tree has turned yellow and apparently will die.

At other times in south Georgia and northern Florida, I have seen where it seemed as if lightning had "searched" for the oak trees and sometimes pine trees were struck and the hardwoods passed by. In one instance near Boston, Georgia, I observed where lightning had struck and killed a loblolly pine tree that was actually growing through the crown of a live oak tree without any damage to the oak. This oak is still alive and thriving several years later. Thus, it seems apparent that the phenomena of lightning is highly variable and perhaps unpredictable.

That lightning can create ecological changes over relatively large areas has also been reported.

> In June 1923, on the Columbia National Forest in Washington a mixed coniferous stand was curiously affected during a severe electrical storm. On a strip of timber about 3 miles long by ¼ mile wide, the needles were partially or completely killed and browned on the trees from the top to within 3 to 50 feet from the ground, and the stand on the strip appeared dead. However, the twigs and buds were not affected, so trees resumed the growth and developed new shoots as usual. Several other similar, though smaller, areas of injury occurred in the same locality. A July storm scorched about twenty-five acres of timber in the same way and killed about three hundred trees outright. In no case were there any outwardly visible lightning wounds on the trees. (Boyce, 1948)

Baxter (1952) reported on "Mechanically uninjured chestnut killed by lightning on the Washington National Forest, Virginia, September 1928." In this example the killed trees were distributed over an area of 70 by 186 feet. He found 4 trees mechanically injured, 43 trees dead but no injury evident, and 14 trees alive and apparently uninjured. He states, "Only a few trees in the vicinity were actually struck, but many were killed."

On August 9, 1966, at 5:15 pm a severe electrical storm passed over Greenwood Plantation, Thomasville, Georgia, and continued for over 15 miles southward. Very shortly thereafter several trees that had been struck were noted. Further investigation provided a very interesting insight to the ecological implications of such storms. About ½ mile from my office where I first witnessed this storm, lightning either became more intense or the storm "hesitated" over an area of about 1 acre in a mature virgin longleaf pine forest. Thirty-two trees were marked and numbered that showed either obvious mechanical damage (only five near one edge of the acre plot) or indicated a scorching of the needles. Five other trees had been struck between my office and this area and seven others were found just to the south.

Three days after the storm, Mr. Gordon Hasty, Millpond plantation, Thomasville, Georgia, some 7 miles due south of Greenwood, reported that this same storm at about the same time had struck a considerable number of trees there, including some in a virgin stand of longleaf and slash pine. Fortunately the storm path followed a road most of the way from Greenwood to the Florida line so that I was able to follow the damage that far—some 15 miles. In this investigation I found a total of 174 trees that showed obvious damage from this one storm. There is no way of telling how many I did not find for I only traveled a very narrow area. Some further inquiry showed that this storm continued striking trees well down into Florida and that it also had been very active well north of Greenwood. Mechanical damage in the form of streaks was found on four species of pine, longleaf, loblolly, shortleaf and slash, but none on any hardwoods, which are interspersed throughout the path of the storm. Damage was found on old mature pine, 300 years old or older, as well as on small saplings probably only 25 years of age. This same storm not only "clustered" at Greenwood but also on Millpond and the Mitchell-Swift farm (part of Greenwood) on the Florida line but in a smaller area. Mr. Hasty informed me that lightning has reduced the virgin stand considerably in the past 25 years or more and that there are only a few trees left in this relatively small area.

The lightning in this storm not only struck large trees but also reached into thick stands of young saplings where it killed from one to six trees. In one instance it only killed one small suppressed longleaf sapling much shorter than its associates within the stand. The obvious injury varied from one longleaf actually being split wide open to only very short narrow "streaks." However, many trees throughout the 15 mile, narrow strip showed considerable discoloration and yellowing of the needles in the crowns. Some of this was observed rather close to or adjacent to trees that had been struck. I believe much of this, which somewhat resembles "needlecast", indicates that such trees were "brushed" with varying amounts of electricity but the voltage or amperage was not sufficient to do more damage. A few of these trees subsequently died but most regained their normal color within the next 18 months.

Lightning Ecology

The "cluster" strike at Greenwood is of considerable importance as it occurred in the virgin forest where this kind of effect has happened before. Another area, also about 1 acre in extent, and in the same forest, had been similarly affected some 8 years previously. This damage occured in a young age class of longleaf pole type timber. Here five trees showed obvious mechanical damage. However, Mr. Leon Neel, our consultant forester marked all the trees that showed any browning of needles or insect attack for this was done quite sometime after the lightning storm had occurred. By this time beetle activity was quite evident. Instead of lumbering the acre we allowed the trees to remain uncut. The only trees that died in this plot were those marked by Mr. Neel. I feel that this damage was largely due to lightning and that the insects were a secondary effect.

Some 16 years ago we observed several lightning struck trees in a block of mature longleaf in this same area. By the time anyone had paid any attention to this, quite a few trees were infected by Ips and other beetles. As it was felt that this might create an Ips outbreak Mr. H. L. Stoddard, our consultant forester at the time, marked the area of about 1 acre and it was lumbered. I believe this again was one of the lightning cluster phenomena.

The longleaf mature forest, like the ponderosa and some other forests, is characterized as a forest of "uneven stand" but made up of small units of "even-age" trees. Upon looking at the Greenwood forest more closely it has been observed that many of these units of "even-age" stands cover an area of about 1 acre; there are a few somewhat larger and a few in long streaks. Is it possible that electrical discharges over long periods of time are an ecological function of these kinds of forest? Does lightning play a regenerative role in the long history of these forests? Unfortunately, both this forest and another somewhat similar one on Millpond Plantation have had much human use—from "rail-splitting" days as well as building material to the present "improvement" cuttings. I believe that close investigation in the ecology of these kinds of forests will show that lightning is an ecological component, a vital force in succession, diversity and continuity, as well as a very important part in the "balance of nature."

That this type of electrical phenomena is not limited to temperate forests is becoming quite clear by studies that are being made in more tropical environs. Brunig (1964) reports in a study of lightning in Sarawak that,

> Lightning gaps covered between 0.5 and 2.6 per cent of the forested area in Alan and Alan bunga forest and about 0.1 or less per cent in the low and dense Padang Alan forest . . . The marked fluctuation in number and area proportion of gaps and associated small wind throws suggest that the lightning damage in this form plays an important part in the development of individual trees and possibly of the *Shorea albida* forest as a whole, which may be accentuated by, the process of a fairly rapid seral development of these forests.

The gaps in these forests varied from .5 to 1.0 acre in size; very similar in this respect to what was found in our longleaf forests. Concerning lightning damage in peat swamp forest in Sarawak Anderson (1964) states,

> 1. The damage (lightning) is most severe in *Shorea albida* consociation, where the canopy is pure and even,, but damage also occurs in the other forest types, though less pronounced or obvious.
> 2. Trees exceeding 50 in number may be killed or damaged by a single strike where the canopy is even, but in forest with an uneven canopy damage is largely confined to emergents and a few middle and lower-storey trees in the vicinity of the killed emergents.
> 3. The intensity of damage is greater at the focal point, which is usually near the centre of the group. Here trees of all storeys, and including saplings and even shrubs and seedlings, may be killed. Towards the perimeter of the group damage decreases and only the canopy trees are likely to be affected . . . .

> Since observing and studying the effects of lightning damage in peat swamp forest, a constant look-out has been kept for similar damage in other forest types. It is, in fact, remarkably frequent. In mangrove forest, especially pure stands of *Rhizophora*, the damage is most pronounced. . . . Typical lightning damage has also frequently been observed in tropical heath forest, . . . In lowland dipterocarp forest damage is less obvious and may be easily overlooked. Nonetheless, it is of frequent occurrence, particularly along ridges.

Anderson (1964) also summarized the following additional reports on group damage in various types of forest:

> Peace (1940) reported an interesting instance of lightning damage in the New Forest in England. About a half dozen trees of 65-year-old Douglas fir, several small beech and one small oak has been killed. Moreover, branches of surrounding trees were affected, and these were invariably on that side of the tree nearest the dead trees—a feature also noted in peat swamps . . . More recently Murray (1958) has recorded severe lightning damage in Scotland. About 100 trees of 45-year-old Japanese larch were killed in a group covering approximately three-quarters of an acre . . . There have been a number of reports from the Continent, especially Germany, where Muller (1938) examined the problem. The phenomena has also been observed in New Zealand, where the New Zealand Forest Department (1954) reported the investigation of group damage in *Pinus radiata* plantations. Twenty groups, each about a quarter to half an acre in area, have been investigated and the damage attributed to lightning.

Group of cluster strikes in other vegetations (rubber, tea, coconut palm, farm crops, etc.) have been summarized previously (Komerek, 1964, 1965). It is evident that this type of electrical discharge is by no means unusual and is of world-wide occurrence.

OTHER LIGHTNING ECOLOGICAL EFFECTS

Several investigators have suggested that the constant bombardment by lightning discharges may have been the direct agent in the evolution of living organisms. Miller (1935) produced several organic compounds by the electrical bombardment of a contained hypothetical primitive ocean and atmosphere. Many similar and successful experiments have since been conducted by others that have duplicated the creation of the "basic building blocks of life." Ponnamperuma and Hodgson (1967) have recently produced an apparent chlorophyll-like substance. Komarek (1965) discussed the possibility of muta-genic changes occurring by this constant bombardment of the earth's surface by variable lightning discharges, particularly at certain critical periods during the reproductive processes (mitosis). Electrical discharges may also have played an important part in the processes outlined by Stebbins (1951).

An interesting side note seen occasionally in the Southeast but more often in western ponderosa, is the number of insects that are trapped in the gum. Quite often in ponderosa but only rarely in the southeastern slash and very rarely in longleaf, the streak made by the electrical discharge will make gum flow quite heavily. In one example near Panacea, Florida, two slash pines that were leaning were damaged on the leaning side. This allowed about ½ pint of the gum to gather at the base of the trees. Over five species of insects were found buried in this gum. Time has not permitted a more thorough examination of the material gathered or for identification of the insects. We have since been able to locate quite a bit of gum at the base of trees that showed such resin flow. In northern Arizona most of the ponderosa that had flowed had small pockets of gum where the streak entered the ground. In many of these the gum was covered with soil and had to be dug out. Likewise, we noted some insects trapped in the dry gum up on the trees. The literature on amber, which is fossil gum, simply remarks that resin is the result of forest fires. As I have yet to see or find a record of trees flowing gum after they have been killed or severely injured by fire, I feel that lightning injury to conifers may be a more logical explanation.

LIGHTNING AS A FIRE AGENT

I have in the past few years discussed lightning as a fire agent in several previously cited papers but particularly for North America (Komarek, 1967). In that paper I pointed out that:

> Lightning fires are an integral part of our environment and though

> they may vary in number in both time and space they are rhythmically in tune with global weather patterns.

Bumstead (1943) has pointed out that even these may be related to such universal phenomena as sunspots.

> The results of this preliminary study indicate that there may be some relationship between sunspots and lightning fires over a large area . . .

In my previously mentioned paper I pointed out that 1961 was the highest critical lightning year in the United States for the past 25 years. Thus, it is interesting to note in this regard the following:

> The weather leading up to and during the Dwellingup fires was the worst on record for the Northern Jarrah Forest Region . . . The area generally experienced a dry year during 1960 with an annual rainfall deficit in excess of five inches . . . In conjunction with . . . above average temperatures heat wave conditions were experienced in the latter part of December, during which month Dwellingup recorded 19 days with temperatures above 80 degrees, with five above 90 degrees and four days of dangerous fire hazard. (Harris, 1962)

From January 19 through January 25, 1961 a series of lightning strikes set fire to and burned over more than 350,000 acres of eucalypt forest in Western Australia. During this period temperatures ranged up to 106 degrees and the area was bombarded with nearly regular occurring electrical storms. Fifteen major fires were set by lightning but this only represents a portion of the fires ignited. The year 1961 was the most critical and severe lightning fire year on record.

In this respect it is interesting to note the following quotation from a recent United States study concerning nationwide critical fire weather patterns (Schroeder, *et. al.* 1966).

> The conditions creating critical fire weather are frequently related to the synoptic weather patterns and cover wide areas. It was no mere coincidence that on the same day in 1871 on which 250 persons and a third of a city were wiped out in the Chicago fire (Musham 1941), 1,500 persons were killed and 1,250,000 acres burned in the Peshtigo fire in Wisconsin, and 2,500,000 acres burned and an undetermined number of people perished in fires

that raced across the lower peninsula of Michigan (Holbrook 1943), (David 1959). Critical fire weather prevailed in the entire Lake States region.

However, it should be pointed out that not only did "critical fire weather prevail" but also over most of this region the forests had been devastated by wasteful lumbering practices for several years. The "waste" in these timbering operations accumulated combustible fuel uniformly over large areas. This was a much greater fuel build-up than could ever occur under natural conditions. In addition, a more combustible mixture than even nature could conceive, were the cities, villages, and farm houses constructed of wood, with wooden shingle roofs, along with wooden sidewalks and sawdust streets. Fire wasn't the culprit; it was man with his absolute disregard for one of the basic laws of nature—the basic principles of combustion "had not been repealed." Even now he still has not learned when spectacular fires occur that perhaps the basic cause of these may be his management over the previous years. The major fires of the past few years where investigated have, without exception been caused by mismanagement by man; by allowing too much highly combustible fuel to *accumulate uniformly over large areas.* The energy release in some of these fires is kin to that of nuclear explosions and cannot be controlled and only sometimes contained. This again is a disregard for another basic principle in nature, *diversity.* However, uniformity is easier to administer (for a short period only.) *Critical fire weather is periodic and recurring.*

CRITICAL FIRE WEATHER

The phrase, "critical fire weather," used by the U.S. Forest Service is based on weather conditions under which severe fires can occur, either by man or by lightning. Man lengthens the critical fire weather period in two ways. He can ignite fuel during periods when there is little or no possiblity of thunderstorms. Excessive fire prevention and lumbering operations can accumulate more continuous highly explosive fuel than would occur under natural conditions.

In the above mentioned study, the United States was divided into 14 "Regional Fire Weather Patterns and Types" based on critical fire weather.

> Recognizing that weather is an important factor in the spread of both urban and wildland fires, a study was made of the synoptic weather patterns and types which produce strong winds, low relative humidities, high temperatures, and lack of rainfall—the conditions conducive to rapid fire spread . . . If critical fire weather periods can be predicted, preparations can be made to counter such disasters and reduce the damage they cause. But before such predictions can be made, the synoptic weather patterns must be identified . . .
>
> As the first step in this study, the 48 contiguous states were grouped into 14 regions, and the periods of critical fire weather were identified for each region. It integrates various weather variables into fire danger indexes, weighing each variable according to its effect upon fire spread and intensity . . .
>
> Once the critical periods were identified, the next step was to determine the synoptic weather types associated with these weather periods. This was done by a study of surface and upper-air weather maps . . . we related most of the periods of high fire danger to a relatively few weather types . . . In some regions of the country the surface weather pattern was the most important. To distinguish them, surface weather conditions are referred to as surface weather *types* and upper-air conditions as *patterns*. (Schroeder, *et al.*, 1964).

Schroeder and his colleagues emphasize:

> . . . this study gives a "broad brush" treatment to the problem of critical fire-weather periods. Only the synoptic scale is considered. Obviously many instances of high fire danger can be found which are not accounted for by the weather types and patterns described in this study . . . The types described here are *periodic*. They occur *over and over again* and account for the vast majority and the most severe of the high fire danger periods. (italics mine)

The fact that these critical "fire weather patterns and types" are periodic and re-occurring is of profound ecological significance. It gives us a reasonable basis for the evolution of fire environments, through natural selection, as well as for the maintenance of *continuity* of the plants and animals adjusted to the fire created stress of such environments. At the same time we must also recognize that in the absence of such needed fire-created stress, *succession* of other living things not so adapted will take place. The inherent variability of fire effects, frequency and intensity and of fire behavior itself, creates *fire mosaics* super-imposed upon these variegated patterns developed by such forces as temperature, moisture, light, soil and topography.

The study by the U.S. Forest Service on "critical fire weather patterns and types" and its meteorlogical and *ecological* implications, points out that:

> Severe burning conditions are dependent upon other factors in addition to weather, notable fuels and topography. At one extreme there is no fire hazard regardless of the weather if there is no fuel to burn. On the other hand, burning conditions may be critical even under less than severe fire weather because of the amount, concentration, type and arrangement of fuels. (Schroeder, et. al. 1966).

In this study the investigators used the Service's "Wildland Fire Danger Rating System" which

> . . . uses a multiple index concept designed to provide the most useful information for planning and carrying out fire prevention, detection and suppression of wildfires. Separate indexes are computed for each major aspect of fire behavior . . . The system provides indexes for grass areas—where only fine fuels are present, for brush areas—where fine and medium-sized fuels are found, and for timber areas—where fine, medium, and heavy fuels exist. In this study only the timber indexes were computed and used. The timber indexes take into account the moisture contents of the heavy fuels as well as the medium and fine dead fuels, and therefore are sensitive to long dry spells and to cumulative precipitation . . .
>
> The concept used in developing a fire intensity index is that, all else being equal, the intensity will vary with the moisture content of medium and heavy fuels. The drier these fuels are, the more of them will become available for combustion and the more quickly they will be consumed. Fine fuel moisture content will also effect fire intensity . . .

REGIONAL FIRE WEATHER PATTERNS AND TYPES

On the basis of these criteria of weather and fuels Schroeder and his colleagues listed 14 "Regional Fire Weather Patterns and Types" as follows:

1. Northeast region
2. Southeast region
3. Lake States region
4. Ohio and Middle Mississippi Valley region
5. West Gulf States region
6. Southern Plains region
7. Northeast Plains region
8. Northwest Plains region
9. Northern Rockies and Northern Intermountain region
10. Central Intermountain region
11. Southwest region
12. Pacific Northwest region
13. Northern and Central California region
14. Southern California region

This is the first example which has come to my attention where the nation or any other sizeable area was divided into more or less homogeneous parts *based on fire-climates and fuels.* In the past, many scientists have divided and mapped the world's plants and animals. Among them are Merriam (1892, 1894, 1899), Shreve (1917), Schantz and Zon (1924), Shelford (1963), Kunchler (1964). All of these looked upon climate as principally a matter of temperature, rainfall, and soils and based their mapping on the basis of *climax* communities. Overlooked was the fact that lightning fires were a component of climate and that these electrical discharges were before man, and still are, a powerful natural force keeping many vegetation and animal associations or communities in a seral stage or more properly a "fire-climax." This was probably caused by the widespread idea that man was primarily responsible for fire and disregarded the fact that many of our vegetation types evolved long before him; the grasslands of central North America are a good example (Komarek, 1965, 1967). Some of these authors have referred to fire but only incidentally to over-all vegetation and animal succession. Shelford (1963) discusses fire effects on communities but not as a *permanent reoccurring dynamic process* in most regions of the continent.

LIGHTNING FIRE BIO-CLIMATIC REGIONS

Recognizing lightning fires as a vital part of climate, I propose the following seven lightning fire bio-climatic regions of North America. Certainly the evidence presented at these past eight Tall Timbers Fire Ecology Conferences, as well as other studies, show that lightning fires are an integral part of our environment. These seven lightning fire bio-climatic regions are:

1. Southern Pine Forest
2. Eastern Deciduous Forest
3. Central Grasslands
4. Boreal Forest
5. Tundra
6. Western Mountain Complex
7. Tropical Evergreen Forest (Rain Forest)

1. Southern Pine Forest lightning fire bio-climatic region.

This region is characterized by four main species of southern pines, longleaf (*Pinus palustris*), shortleaf (*P. echinata*), loblolly (*P. taeda*), and slash (*P. elliotì*). All are adjusted to fire of various recurring intervals and intensities. This region is usually considered as part of the temperate deciduous forest by most botanical investigators including Shelford (1963) and Braun (1940). This *is only valid in the absence of fire*. In the absence of fire the pine forests will develop into a magnolia (*Magnolia grandiflora*) and beech (*Fagus grandifolia*) forest even on the tops of the highest red clay hills in the Tallahassee Redhill section of Florida, and are only restricted to lowlands because of the regular occurrence of fire (Kurz, 1945). This coastal plains region has the *highest known incidence of thunderstorms* of any region of North America and contains one of the most fire resistant and fire-adjusted forests.

These southern pine forests have characteristic herbaceous, leguminous, and grass ground cover where regularly burned, much like the prairie flora. It is a pleistocene relic grassland that covered the Southeast extensively and was the habitat of a rich extensive mammal fauna. It is a fire-climax even more adjusted and responsive to fire

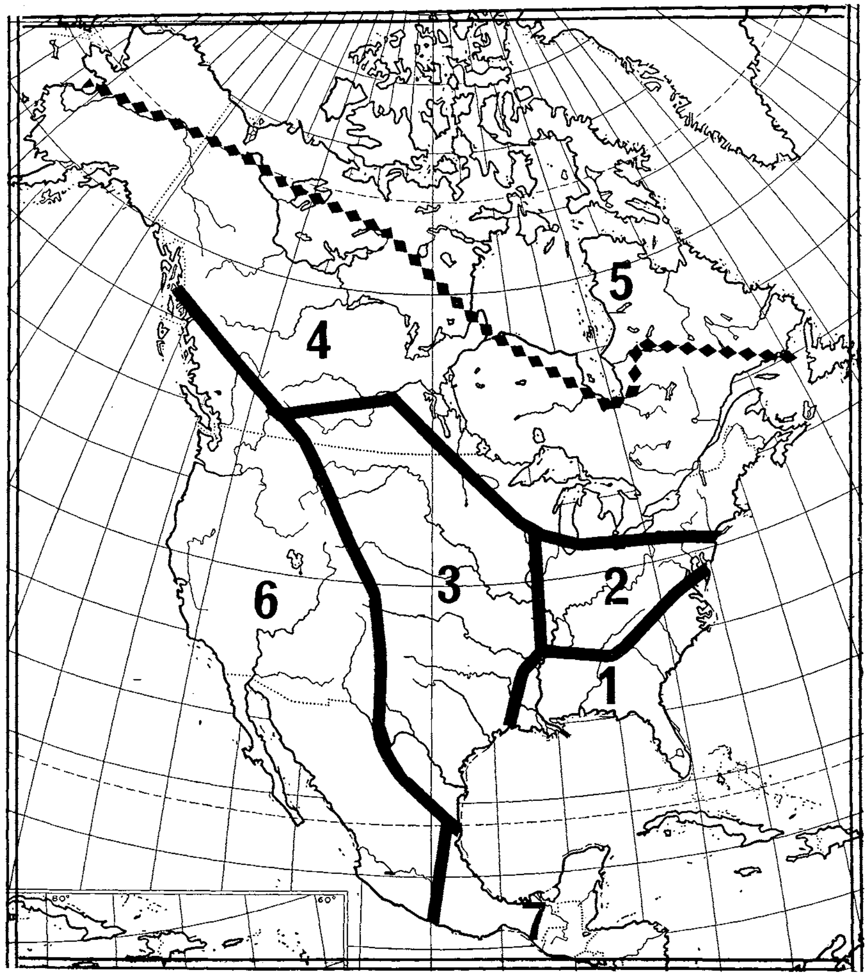

FIG. 3. Diagrammatic and provisional lightning fire bio-climatic regions of North America. 1. Southern Pine Forest; 2. Eastern Deciduous Forest; 3. Central Grasslands; 4. Boreal Forest; 5. Tundra; 6. Western Mountain Complex; 7. Tropical Evergreen Forest (Rain Forest).

than the pine forest which shades it but slightly. In the asbence of fire these are replaced with a thicket of various species of hardwoods. At Tall Timbers Research Station this prairie ground cover has disappeared within seven years of fire protection on experimental plots.

This prairie ground cover along with the pine needles makes a highly combustible fuel combination, in comparison to the ground cover of the eastern deciduous forest. Nearly all summer rainfall in this region is from thunderstorms, with the precipitation irregular in amount and distribution. Dry spells occur in late spring and early fall and severe droughts quite frequently.

Probably considering man's influence on the native vegetations, Shroeder, *et al.*, divided this region into a West Gulf States and a Southeast on the basis of critical fire weather, and extended it northward to include the Applachian Mountains which floristically belong with the Eastern Temperate Deciduous Forest.

2. Eastern Deciduous Forest lightning fire bio-climatic region.

This region is characterized by a dense hardwood forest that if undisturbed, develops into a beech (*Fagus* sp.) and maple (*Acer* sp.) climax. Both beech and maple are not very resistant to fire except to light fires at maturity. However, throughout the eastern deciduous forest northern area as delimited by Braun (1940), there are species such as the white pine (*Pinus strobus*) that are adjusted to fire. The original stands of white pine occurred on areas that had burnt and the species requires mineral soil on which to germinate and grow.

The ground cover is very poor, in comparison to the southeastern pine forest, and consists largely of forbs that are not too well adjusted to fire. The leaves of the hardwoods become closely packed to the ground and will only burn under very dry conditions so that conditions for fire to spread must be severe.

The rainfall is well distributed throughout the year, both by thunderstorms and general frontal activity. There is considerable lightning in this region but the rainfall patterns are such as to prohibit extensive fires except during the infrequent droughts or by conditions created by man. There is a wide tension zone between this region, both to the south as well as to the north. In fact, Schroeder, *et al.*, separate the Lake States region from the deciduous forest on the basis of critical fire weather. However, for the present, I prefer to call it a tension zone between the boreal forest and the eastern deciduous forest.

3. Central Grasslands lightning fire bio-climatic region.

The central grasslands of North America are the largest continuous grasslands in the world. They extend from Mexico to the far north from longitude of about 95 degrees eastward to about 105 to 110 westward with outlying areas both east and west. The elevation extends from sea level to only about 1000 feet above in the Northwest Territory, Canada. Because of its location eastward of the Rocky Mountain Ranges, it is a region of intense thunderstorm activity. The vegetation consists of tall grass prairie with a mixture of forbs eastward from the 100th meridian, to a short grass prairie rather limited in forms, westward. In both sections occur a great many grasses, etc., that are well adjusted to fire conditions.

The ground cover consisting of tall and short grasses is highly flammable. This factor coupled with relatively small amounts of rainfall, erratic weather patterns, many severe dry lightning storms, and recurring droughts all adds up to a highly critical fire environment. Because of its great extent, with few barriers and high sustained winds, fires were quite widespread originally.

All along the eastern border of the grasslands from the Gulf coast northward there is a wide tension zone consisting of parklands made up of several species of oaks which in some areas are replaced by aspen (*Populus*). Along the western border the tension zone consists of various species of oaks and parklike forests of ponderosa pine, all of which are well adapted to fire. In the absence of fire in both of the tension zones the grass gives way to bushland such as mesquite (*Acacia* sp.), Juniper (*Juniperus* sp.) and pinyon type pines (*Pinus* sp.), most of which have developed many various mechanisms to protect them from occasional or light fires. A few species are quite fire resistant.

Schroeder *et al.*, have three divisions in this region—a southern, eastern and western. Here again, I prefer to consider the various edge effects as tension zones. However, in many instances several species of hardwood and pine trees occur along rivers and streams where they are well protected from too frequent fires. All of these have some fire adjustments in their habits.

4. Boreal Forest lightning fire bio-climatic region.

The region consists of a broad band primarily of white and black spruce (*Picea glauca* and *P. mariana*) from the Atlantic to the Pacific Oceans. The trees themselves are not very fire resistant and will only tolerate very light fires when mature. The ground cover made up of forbs and mosses becomes highly flammable during dry periods. The branches of these trees also reach close to the ground so that crown fires can readily develop when conditions are suitable. However, catastrophic fires are necessary for regeneration of species of spruce.

Before man's interference, originally lightning created a very fine detailed fire mosaic in most of this region. Now in some areas, because of extensive lumbering and uncontrolled man-caused wildfires, much of the region is blanketed with a uniform forest cover that is highly flammable under drought condition. Under such conditions, fires can be widespread indeed, but I believe this is due to man's destruction of the original lightning mosaic.

The region is characterized with only moderate rainfall, a relatively short thunderstorm period, but with much thunderstorm activity and dry lightning storms.

5. Tundra lightning fire bio-climatic region.

The tundra region is well known as a frozen desert but in many fire respects, it resembles the grasslands. Winds have a wide sweep and under dry conditions the vegetation is very flammable. This makes for widespread fires. The thunderstorm period is relatively short although it can be intense. Certain plant species in some respects act like the spruce forests, that is, when once burnt they may take many years to regenerate. However, I have suggested that the caribou nomadic habit may be a response to the original widespread lightning fires.

6. Western Mountain lightning fire bio-climatic region.

The westernmost part of North America consists of extremely varied topography, from high mountain ranges, isolated mountains, to hot dry vallys and basins. Because of the great range in elevation the region is "zoned" and in many respects resembles the vegetations characterized in the previous four regions but compressed in narrow bands. This area is essentially a cross section of most of the climatic regions of the continent. Thus, the vegetation ranges from species highly resistant or adjusted to fire to very fire tender communities. Rainfall is erratic and nearly all summer precipitation is from thunderstorms and ranges from desert-like conditions to the very moist forests of the northwestern coast. It is a very complex region not only for plants and animals but also for fire effects and behavior. The ponderosa pine forest resembles the southern pine forests in many respects as to habits as well as adjustments to fire.

7. Tropical evergreen rain forest lightning fire bio-climatic region.

These forests are characterized by very little ground cover that will burn, for most of the litter is utilized very quickly by the many organisms that live in such environments. They are found in regions of very heavy and well distributed rainfall. Fire effects in the genuine rain forest appear to be few. However, man's activities have allowed fire to destroy this type of forest. This is caused by destruction of the forest for agriculture and then replacing the open ground with grasses, usually exotic species, that are highly flammable. When these are burned the fire scorches, injures, and kills the fire tender forest vegetation along the edges, thus allowing grass to encroach upon the forest.

These forests are, however, subject to intense and great amounts of lightning activity and I believe the direct effects of lightning have an ecological place in the regeneration of these rain forests.

SUMMARY

In this paper on lightning and lightning fires as ecological forces I have reviewed and summarized the information that leads to the belief that

1. Lightning is of considerable importance and significance in the ecology of forests. Its action as a "predator" of trees assist in the regeneration of certain forest types. The trees that are struck by the various lightning effects play a large role in the ecology of certain forest insects and birds that prey upon them.

2. Lightning fires are a very necessary part of the "natural" environment and these were of great ecological significance in the development of the North American plant and animal associations. On the basis that lightning fires were an integral part of this environment I have designated the following lightning fire bio-climatic regions of North America.

1. Southern Pine Forest
2. Eastern Deciduous Forest
3. Central Grasslands
4. Boreal Forest
5. Tundra
6. Western Mountain Complex
7. Tropical Evergreen Forest (Rain Forest)

Further studies will undoubtedly develop various subdivisions of these.

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