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Wildland Fires

Predicting the behavior of wildland fires—among nature's most potent forces—can save lives, money, and natural resources

During a period of three days in mid-February 1983, bushfires swept over 400,000 ha in southern Australia, killing 74 people, destroying more than 2,000 homes, and burning out 7 towns. This tragic repetition of the fires of January 1939, in which 71 people perished, was foretold by Noble (1977), whose monograph on the 1939 fires ended with a chapter entitled "It Can Happen Again." Ecologists familiar with the cycle of wildfire in such ecosystems assert that fires like these will recur.

Although the United States has been spared such catastrophic losses to wildland fire in the recent past, in this country an average of 130,000 fires burn about 10^6 ha every year, and similar figures apply to Canada (Harrington 1982). About 90% of these fires are started by human activity, and thus most represent "unnatural" but powerful forces for ecological change for which we are collectively responsible. Good luck may have helped keep America's wildfire losses in check, but efforts to control fires have also been extensive and increasingly effective.

Until relatively recently, the United States was unswervingly committed to suppressing wildland fires. The expenditure by the USDA Forest Service alone for fighting forest fires and maintaining its readiness to do so rose steadily to an annual high of more than $300 million in the mid-1970s. Fire prevention programs were extended, fire detection became more efficient, and the technology used to suppress fires continued to advance (Fig. 1), all at increasing cost. Wildland fire research was also expanded, with the establishment of three Forest Service fire laboratories between 1959 and 1961 making more sophisticated experiments possible.

Efforts to base a policy of controlling wildland fires on economic analysis have been mounted repeatedly (USDA For. Serv., unpubl.), and the subject is a matter of current research. However, economists have yet to agree on a satisfactory method for calculating the economic costs of disruptions and dislocations by fires in the flows of benefits from publicly owned lands. Prior methods have been discredited as overstating the economic costs of fires; the fire management policy now in force emphasizes economic efficiency (USDA For. Serv. 1978).

Concurrent with a rising concern for the cost of fire control, ecologists, foresters, and land managers in growing numbers came to view attempts to exclude fire from much of America's wildlands as unwise and, ultimately, probably futile (Ahlgren and Ahlgren 1960; Cooper 1961; Leopold et al. 1963). As a natural component of forest and range ecosystems, fire can retard, advance, or maintain the stage of ecological succession at a specific site. The combustion of living and dead plant matter releases not only heat but also mineral nutrients like ash and carbon in the form of carbon dioxide for recycling as new plant growth. In combination, these effects can trigger the release of seed, prepare seedbeds, and reduce competition among plants for moisture, nutrients, and light. By these mechanisms, fire can be used to manipulate the distribution of species and of ages of plants within an ecosystem in order to accomplish such goals as providing a suitable habitat for wildlife or forage for livestock. Fire can also be a means of controlling the propagation of insects and plant disease. Although fires of high intensity can eradicate all plant life and, by damaging topsoil, can even be detrimental to the productivity of a site, low-intensity fires can be beneficial (Soc. of Am. Foresters 1984). Often prescribed burning—controlled burning under specific conditions—is used to reduce the amount of accumulated fuels and thus to preclude later destructive high-intensity wildfires.

The fire policies of all major land-managing agencies of the federal government now acknowledge the potential ecological benefits of some wildland fires and allow the use of prescribed fires. These policies extend to national parks and to wilderness areas, in which fires ignited by lightning are not suppressed if the conditions are deemed appropriate.

These new policies have profound implications for wildland fire research. Land managers must now make quantitative predictions of the effects of prescribed fires, assess the economic implications of alternative suppression strategies for wildfires, and make long-term projections of the growth, behavior, and effects of naturally occurring fires that are allowed to continue burning in designated areas. Such evaluations require a rich fund of knowledge about methods of suppressing wildfires, economic assessment, fire behavior, and fire effects. This paper will focus on the current state of knowledge about the behavior of wildland fires. Recent works by Pyne (1982) and by Chandler and his colleagues (1983) provide informed introductions to the related topics.

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Describing wildland fire behavior

The term *behavior* applied to a wildland fire implies a set of characteristics that describe the rate of the fire's spread, the fuel strata it consumes, the overall shape of its perimeter, its rate of energy release along the perimeter, its mode of propagation, and perhaps the geometry of the flames along the perimeter. The needs of the fire fighter and the land manager for information about a fire's behavior can often be satisfied by a partial description involving some of these variables, but fire research includes the entire range of information and is now concentrated on the development and implementation of predictive models for all these characteristics.

Many of the variables can be derived from the rate of fire spread in the direction of its fastest movement (Albini 1976). Knowing this value and the speed of the wind, spread rates along the fire's flanks and against the wind can be estimated from empirical formulas that describe fire shape. Multiplying the spread rate by the mass of fuel consumed per unit area, as seen from the air, and by the heat of combustion of the fuel gives the energy release rate per unit length of the fire's edge, or the intensity of the blaze. There are also theoretical models and empirical formulas that link fire intensity, wind speed, flame geometry, and so forth. Consequently, much effort has been expended in the quest to model the maximal spread rates of fires in wildland fuels.

Wildland fires are loosely classified in terms of the fuel strata through which they principally spread. They are all considered free-burning fires—fires not confined to one location—but their rates of movement are fixed by conditions in one of three fuel strata. Ground fires occur in the subsurface organic material of such ecosystems as peat bogs and swamps, in organic soils like those found in the coastal Southeast, or in the humus layer of most forest floors. Surface fires are those in forest litter, trees and branches that have fallen because of age or decay, and surface vegetation. Crown fires burn in the tops of standing trees, moving from tree to tree.

Some specialists classify fires in shrub fields such as southwestern chaparral as crown fires because, technically, the fires spread principally through the crowns of the shrubs. For the purpose of this discussion, however, we shall classify such fires, as well as fires involving only the understory or in stands containing only juvenile trees of short stature, as surface fires and use the term *timber crown fire* for those blazes that spread through the crown layers of established stands of trees. Such stands often exhibit a distinct crown layer separated vertically from fuels in the understory and on the surface, but some species of trees (such as firs and spruces) may have crowns that extend to the ground. In many mature stands there is no appreciable surface fuel other than litter and woody debris from the trees.

Ground fires spread mostly by smoldering combustion at the rate of a few centimeters per hour, often with little or no surface evidence of their presence save for an occasional wisp of smoke. Such fires can be very destructive, killing the roots of trees and the communities of organisms that form the symbiotic network of the living forest floor. They are usually very difficult to extinguish and can burn for months without being detected, sometimes kindling surface fires when conditions become favorable for the burning of surface fuels.

They can be started by spontaneous combustion or, more likely, by lightning, but ground fires are often ignited by surface fires. A surface fire can burn through the upper layers of litter and duff—the partly decayed organic matter on the forest floor—to start a smoldering fire over a large area of the humus layer. This can occur when all the organic material is quite dry, as is often the case after a long period of dry weather. At other times, fire may consume a layer of litter without igniting the wet humus on which it rests; this occurs frequently in the spring and early

Figure 1. A specially equipped helicopter can quickly reach a remote wildland fire with flame-retardant chemical salt in a water solution; the fire shown here occurred near Lake Chelan, Washington, in 1970. The solution also contains a red dye so that the area where it has been applied can be identified from the air. Fire-fighting technology has steadily improved, keeping down fire losses but increasing the costs of controlling fires. (Photograph courtesy of C. George.)

summer, when the lower layers have not had time to dry out. Once started, however, ground fires can smolder through organic matter that is remarkably moist. Fires in the laboratory have burned peat moss with a moisture content of 90%.

Decaying woody material, especially rotting fallen trees, provides pathways for fire to spread between surface and subsurface fuels. Dry, rotten wood is quite readily ignited; a minute spark from an engine exhaust or an ember from a lighted cigarette can be sufficient to start a smoldering fire in such fuel. Ground fires ignited by a surface fire often persist in the area long after the surface fire has been extinguished. A light rainfall may extinguish a surface fire but leave a ground fire burning that will surface again when the exposed fuels dry out. To prevent such recurrences, much work may be required to put out ground fires, even after the flames have been extinguished.

Surface fires like the one shown in Figure 2 are the most common of wildland fires by far, and they exhibit the widest range of behavior of the three types. Their variety is partly because they are sensitive to wind speed and the moisture content of their fuel, and partly because there are great differences between types of surface fuels. A fire in compact litter can creep through the forest at 10 m/hr with an intensity on the order of 1 kW/m when burning conditions are marginal. Under "good" burning conditions, fires race through the chaparral fields of southern California at speeds up to 10 km/hr, with intensities of the magnitude of 10 MW/m. Grass fires have been clocked at even faster speeds (up to 20 km/hr), but their intensities are typically an order of magnitude smaller; debris from timber harvests may burn with the intensity of a chaparral fire but at a spread rate an order of magnitude lower. The high rates of spread of fires in grass and similar "flashy" fuels, and the responsiveness of these fires to shifts in the speed and direction of the wind, make them the most common killers of fire fighters and anyone else in their paths (Wilson 1977).

Figure 2. Wildland fires are classified in terms of the fuel strata through which they spread. The most common type is the surface fire, which burns vegetation such as grasses and shrubs, as well as litter on the forest floor. This photograph shows a prescribed fire that was set in Glacier National Park, Montana, in 1983. A second type, the ground fire, burns by smoldering combustion in subsurface fuels like peat and organic soils; timber crown fires, the third type, spread through the tops of trees. (Photograph courtesy of B. Kilgore.)

Surface fires exhibit an equally wide range of physical and biological effects. A creeping fire in forest litter in the spring of the year may leave almost no persistent trace of its occurrence. In contrast, a fire in the same area that starts late in the summer might burn not only the litter, but also shrubs, the understory, and fallen branches, producing an intensity several orders of magnitude greater. Such a fire might kill all the trees of the overstory by lethally scorching their foliage, which could leave the area scarred for many years. It is because the effects of fire can vary so much with changes in burning conditions that prescribed fires can be used by land managers to accomplish a great variety of objectives.

Timber crown fires are relatively rare and usually short-lived events (Fig. 3). They are invariably started by surface fires and usually propagate only if there is a concurrent surface fire (Van Wagner 1977), but instances of crown fires propagating on their own have been recorded. Surface fires can sporadically ignite the crowns of trees, singly or in small groups, but this kind of fire behavior is usually described as "torching" or "crowning out" and is not considered to be a crown fire. Timber crown fires are spectacular and highly dangerous. At the "head" or front of such a fire, flames can extend several tree heights above the top of the stand. Radiation from this wall of flame can produce painful burns on exposed skin at more than 100 m from the edge of the fire. The noise from this type of fire has been likened to the sound of many speeding trains passing simultaneously. The heat release rate at the front of the well-documented 1967 Sundance Fire in northern Idaho has been estimated at $\cong 10^5$ MW for a six-hour period (Anderson 1968), yielding an amount of energy equivalent to that of a 200-kiloton nuclear weapon. This fire exhibited a maximum rate of spread of about 10 km/hr, and averaged 2.8 km/hr over the nine hours during which it burned more than 20,000 ha.

Wildland fires can also propagate by "spotting," a mode that does not depend on the continuity of spreading through any fuel stratum. Spotting occurs when a fire produces sparks or embers that are carried by the wind to start new fires too far from the main fire to have been ignited by it directly. The likelihood that spot fires will occur depends strongly on the moisture content of the fine, dead fuels that are most easily ignited. Such fuels rapidly attain moisture equilibrium with the atmosphere, and thus if the relative humidity is high they are unlikely to be set on fire by a small ember or flaming particle. However, when the relative humidity is low and there is a substantial wind, spotting may occur. Planners of prescribed fires must always consider the possibility of spotting, which might allow a fire to burn beyond its intended boundaries.

Potential firebrands are abundant in any wildland setting, raising special hazards when there are strong vertical air currents that can lift them high into the wind stream. The convection column above a fire burning in heavy fuels such as fallen trees that have accumulated in a ravine, and the transitory strong updraft caused when the foliage of a standing tree burns are examples of how firebrands can be transported. Of course, the front of any intense fire that is being driven by wind can give rise to firebrands as well. Timber crown fires can spawn spot fires tens of kilometers away under the right conditions.

Since it is impractical to prevent the generation and transport of firebrands, the alternatives open to fire fighters are prompt suppression of spot fires while they are still small, and elimination of all fuel far enough ahead of an advancing fire to keep it from spotting beyond the fuel-free area. This second tactic consists of deliberately burning off the fuel ahead of a fire by lighting a backfire along a perimeter established by the fire fighters. However, if the wind changes direction unexpectedly before the fires join, the situation may be worse than it was before. And if unanticipated rainfall extinguishes both fires before they join, the incongruous unburned area between them is a reminder of the uncertainties inherent in wildland fire fighting.

Predicting fire behavior

Although many areas of scientific ignorance about wildland fire behavior and effects remain, the state of knowledge has advanced significantly in the past two decades (Chandler et al. 1983; Emmons 1964; Konev 1977; Luke and McArthur 1978). Motivation for research in the field has broadened over this time from the desire to suppress all fires and now includes the goals of improving the cost, safety, and effectiveness of fire use and of more accurately predicting the long-term growth and effects of natural fires allowed to burn in remote areas.

The focus of most wildland fire research has been on surface fire phenomenology, but this emphasis is shifting to accommodate the new motivations. The behavior of surface fires in many fuels can now be predicted successfully (Rothermel 1983); work is currently under way on estimating the behavior and effects of ground fires, and some progress has been made in modeling the onset and propagation of timber crown fires (Kurbatskiy and Telitsin 1977; Van Wagner 1977).

Prediction of the rate of spread, intensity, and flame length at the front of a surface fire, as well as the area burned and the length of the fire's perimeter, can be made in the field with the aid of a specially equipped pocket calculator. The device can also be used to calculate such variables as the maximum spotting distance to be expected and the time needed for a given work force to contain a small fire. These capabilities are the result of a continuing research effort that has lasted more than 20 years, one of whose landmarks was Rothermel's (1972) development of a model that predicts the rate of spread of a surface fire. A combination of perceptive idealization, innovative experimental techniques, bold extrapolation, and luck led to this achievement. A brief review of the work that culminated in the model will illustrate the com-

Figure 3. Timber crown fires are relatively rare, but they are spectacular and highly destructive. Spreading as rapidly as 10 km/hr, they release great amounts of heat. The fire shown here – an experimental blaze set in insect-damaged balsam firs near Aubinadong, Ontario, in 1982 – is so intense that the flames are virtually erect, in spite of the wind blowing directly toward the camera from the fire. The heat of the flames prevents the smoke from obscuring this view of the approaching fire front. (Photograph courtesy of B. J. Stocks.)

plexity of the problem and describe some concepts that have been widely used in attacking it.

The process by which a surface fire spreads can be considered to be a series of ignitions of the particles of fuel that are burned at or near the fire's leading edge. (The larger pieces of woody fuel and the deeper layers of litter and duff that ignite and burn only after the passage of the fire's front can be disregarded because they play no part in the spread process.) A particle of vegetable matter is ignited when it becomes so hot that its thermal decomposition provides enough combustible gases to maintain a flame attached to its surface. This state has been shown empirically to occur when the surface temperature reaches about 325° C. If a piece of fuel has a sufficiently large ratio of surface area to volume, and if it is heated slowly enough, the temperature at the coldest part of its interior will not differ much from its surface temperature. The fine fuels that govern the spread of wildland fires satisfy these conditions. Consequently, the energy (Q) required to ignite a unit volume of a fuel bed composed of such "thermally thin" particles can be accurately computed from the moisture content and physical properties of the particles, and the mass of fuel per unit volume of fuel bed.

If a fire spreads at a steady rate (R) through a fuel bed composed of uniformly distributed, thermally thin particles, then a heat (Q) must be absorbed by each unit volume of the bed as the flame front reaches it. The product RQ thus represents the net rate of energy flux from the burning zone of the fire to the fuel bed in front of it, measured in a plane perpendicular to the direction of advance of the fire's edge. Heat must be transferred from the burning zone and the flame structure to the fuel bed at this rate for the fire to advance at the steady rate R. Theoretical considerations or empirical relations must be used to calculate RQ, based on the properties of the fuel bed, the wind speed, the slope of the terrain, and perhaps the rate of the fire's spread, to "close" the set of equations and thus obtain a predictive model of the process.

The front of a free-burning fire in surface fuels can be approximated as being two-dimensional, extending to infinity in a straight line toward each flank. This idealization is called a line fire. In the spirit of such an approximation, Rothermel postulated that any reasonably uniform bed of fuel could be represented by an equivalent one that would burn with the same spread rate and intensity but would be much simpler to describe mathematically. The hypothetical equivalent bed was assumed to consist of only two types of fuel particles, one live and one dead, with the particles uniformly distributed throughout the homogeneous bed. The mass of each type of particle per unit volume of fuel bed—as well as the attributes of each, including moisture content and surface/volume ratio—was postulated to be calculable as a weighted average of the equivalent properties of the constituents of the actual fuel bed. Finally, he reasoned that studying how fire spreads in fuel beds with only one type of particle and summing, by an appropriate algebra, the contributions that would be made by each of the two particle types to energy absorption and heat transfer should provide the relations needed to close a general model of fire spread.

The pivotal step in the development of the model was the inspired conjecture that the dimensionless quantity formed by the ratio of E, the average rate of heat release per unit area of ground at the front edge of the fire, to the heat flux required to propagate the fire, RQ, should be a function only of the geometric properties of the fuel bed, the wind speed, and the angle of the slope on which the fire is burning. The parameter E is easily measured for fires that do not spread, since in this case it is simply the product of the fuel's heat of combustion and the rate at which fuel is consumed per unit area burning; it has often been used to characterize the vigor of burning of stationary fires. To measure it in a spreading fire required developing a technique for continuously weighing a segment of a fuel bed and carefully interpreting the derivative of the resulting record of weight versus time.

A large number of experimental fires were studied, both in still air and in a wind tunnel, using fuel particles of different sizes in beds of various depth, compactness, and moisture content. From these data Rothermel fashioned empirical equations that yield not only the ratio E/RQ but also E alone. Finally the model was generalized by postulating both the equations necessary to reduce a complex mixture of various sized particles to an equivalent bed of uniformly sized particles, and the algebra needed to combine live and dead fuels.

Since all available laboratory and field data were used in formulating the model, no data remained against which it could be adequately tested. Widely disseminated to researchers as a package of computer programs, it also became the basis for a revision of the National Fire Danger Rating System used by state and federal fire protection agencies throughout the United States (Burgan et al. 1977). The resulting practical tests confirmed that the model was properly sensitive to weather and fuel variables but could not adequately evaluate its predictive accuracy.

After a period of tentative testing against chance data, and with a few minor revisions, the model was made available in a form suitable for use in the field (Albini 1976). It has proved to be far more broadly applicable, even with its known shortcomings, than was anticipated when it was released. At present an expanded set of experiments is being carried out to provide the basis for an independent reformulation of the model. As these data accumulate it is becoming clear that some of the model's empirical relations must be revised, but its basic structure appears at this point to be sound.

In recounting the development of the Rothermel model, the contributions of numerous other investigators have been omitted for the sake of brevity. The recently published comprehensive treatment of wildland fire science by Chandler and his colleagues (1983), and the surveys cited in that volume, should be consulted for a more balanced presentation of the work in this field.

Application of the Rothermel model would have been restricted to the research community had the user been required to provide all the data needed for each use. However, users have been provided with a collection of data sets, each of which represents a complex of wildland fuels common to some region of the United States; by this means most of the variables describing fuel beds do not need to be specified every time. A computer

Figure 4. Fire whirls, vertical vortices in the air that are intensified by a fire, occur quite frequently, often lifting and scattering burning debris and thus starting new fires. Occasionally becoming as intense as a tornado, they can be very destructive. This slowly rotating whirl is from a prescribed fire set to reduce the debris left by a timber harvest before reseeding the land. (Photograph courtesy of USDA Forest Service, Northern Forest Fire Laboratory.)

program to help users in preparing fuel descriptions for situations that do not match any of the standard data sets well is also being developed.

Poorly understood phenomena

A large number of wildland fire phenomena continue to elude theoretical description, and in a few cases it is unclear even what mechanisms are involved. For instance, dead grass will seldom support a spreading fire when the moisture content of the grass is above 15–20%, nor will forest litter if it contains more than about 30% moisture. Yet stands of chaparral composed predominantly of live foliage and stems, and timber stands with virtually all live foliage, can burn with great vigor at a foliar moisture content of 100%. Is this because the fuel beds are deeper and the flames taller for such fuels, or are other factors involved? Attempts to relate differences in flammability to intrinsic chemical properties of fuels have failed to explain the different sensitivities to moisture content. Experimental fires in the laboratory using manufactured fuels have revealed that the geometry of the bed (the size of the fuel particles and the total mass of fuel per unit area) has a very strong influence on the probability that a fire will spread as a function of the fuel's moisture content (Wilson, pers. com.). But since this finding is at variance with anecdotal evidence from experienced field personnel, its meaning is still unclear.

Another little-understood phenomenon occurs when a fire burns on a steep slope with the fire edge roughly following a contour of constant elevation. Sometimes the plume—the products of combustion and entrained air—becomes "trapped," flowing upward along the slope for a considerable distance, like a boundary layer, before detaching and rising more or less vertically. At other times, the plume separates from the slope at or very near the fire edge. A reliable method of predicting when the hot plume would be trapped could prevent lethal scorching of tree crowns far upslope from a prescribed fire. This problem has not been treated analytically to my knowledge, but experimental results suggest that there may be a critical angle of slope above which the plume will always be trapped (Manins, pers. com.).

Transient behavior of wildland fires, in response to varying wind speed, while adjusting to a change in the nature of the fuel, or in the transition period between ignition and development of a steady rate of spread, is not well understood. A phenomenological model for the behavior of a surface fire in unsteady wind has been used to derive spread rate and intensity variations produced by typically gusty surface winds. The model gives acceptable steady state limits and heuristically satisfying transient responses, but it has not yet been tested with any experimental data. Nonetheless, the model has been used to predict the strengths of line thermals—rising bodies of hot air idealized as being two-dimensional—generated by a wind-driven line fire and hence the distance over which live firebrands

Figure 5. The light bands in this aerial view are the unburned crowns of conifers that were only scorched in a timber crown fire near Mio, Michigan, in 1980 which blackened the rest of the region; the photograph shows an area about 1.5 km wide and 3 km long. The fire that burned the surface fuels within the light bands was driven by winds of opposite direction on each side of the bands, as though the winds blew from the center of each band toward both sides. (Photograph courtesy of D. Haines.)

might be carried from such a source (Albini 1983).

Luke and McArthur (1978) described the time between ignition and a steady rate of spread as a fire's "buildup" period, and they suggested a general form for the variation of spread rate during this period, based on field experience. But no theoretical description of the early phase of fire development has been put forward yet, in spite of the fact that in some cases the buildup period is the only time when a fire can be suppressed.

The general pattern of growth of free-burning fires has been codified empirically (Anderson 1983), although not theoretically. The roughly elliptical shapes of large, severe fires mimic surprisingly well the forms of small fires in pine litter in early wind-tunnel experiments, suggesting that the way fires grow is not determined by scale. Indeed, Anderson and his colleagues (1982) showed that if each point on the perimeter of a large fire is considered to be an ignition point for a new fire that grows with the shape and orientation of the original perimeter, the result is a larger fire of the same shape. But as yet no mechanism of growth has been postulated that would justify such a method of computation, nor has the elliptical shape been predicted theoretically.

Fire whirls, vertically oriented vortices like dust devils that are localized and intensified by a blaze, are ubiquitous in wildland fires (Fig. 4). During the Sundance Fire, whirls are thought to have uprooted mature timber in front of the fire and to have contributed to multiple spot fires started by burning material scattered 15–20 km ahead of the blaze (Anderson 1968). Although large, intense vortices are most often associated with large, high-energy fires, whirls of surprisingly high intensity and longevity have occurred in small fires feeding on light fuels.

Whirls are readily generated in the laboratory. Lee and Garris (1969) predicted mathematically the amount of ambient vorticity needed to induce whirl formation along a line fire of given intensity. Their experimental data confirmed this criterion, and they produced multiple whirls in line fires separated by distances predicted by the theory. It is still not clear, however, which factors determine whether or not a whirl will remain in the vicinity of a fire and so become more intense.

Once a whirl is established in a burning area it can act as a natural chimney, providing a low-pressure pathway for the hot gases from the fire. If it stays in place, the whirl intensifies as the induced radial flow toward its base concentrates the atmospheric vorticity. This process has been demonstrated on a large scale—10^3 MW—with an array of large, oil-fired burners called the Meteotron (Church et al. 1980). At the other extreme, Emori and Saito (1982) used a 1:2,500 scale model and a small electrical heater to recreate a 1977 fire whirl that seriously injured fire fighters on Mount Nuki, Japan.

A distinctive pattern of unburned tree crowns has been noted in several instances after a timber crown fire has burned over an area: as shown in Figure 5, the unburned crowns form strips that appear to outline the perimeter of the fire at different stages of its existence (Wade and Ward 1973; Simard et al. 1982). Haines (1982) documented nine instances of such patterns in timber crown fires and several cases in surface fires. However, it is most unlikely that the unburned strips actually do outline the fire edge at different times. Several strips include the head and both flanks of the fire, and if these strips marked the fire's perimeter at one time, the fire would seem to have suddenly died at that moment, a most remarkable incident that would probably not have gone unnoticed.

A puzzling feature of the unburned crown strips studied by Haines is the distinctive pattern of charring of the tree bark within the strips. The trunk of a tree is charred by a surface fire to a much greater height on its lee side than on its windward side. The marks Haines found were left by a fire in the surface fuels under the unburned crowns that was influenced by wind blowing away from the center of the strips. That is, the surface winds were in opposite directions only a meter or so apart.

Haines discussed various alternative theories for the sequence of events and their causes, but he showed that most of the explanations are self-contradictory or inconsistent with other evidence. He speculated that the horizontal roll vortices almost always present in the atmosphere near the surface in a steady wind could have been responsible; a mechanistic description of the connection has not yet been formulated. The cause of these patterns thus remains mysterious, nor is it known if they are associated only with high-intensity fires.

This is only the most recent mystery posed by the phenomenology of wildland fire behavior. The list of poorly understood phenomena can be expected to lengthen for some time to come because research in this field is still in its infancy. As the base of knowledge grows, new puzzles will emerge, and explanations that were once accepted will be challenged as their implications are explored. But useful results have been produced from the present level of understanding, and continued research should yield substantial rewards in terms of safer, more economical control and use of wildland fire.

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