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**SYNTHESIS ON CROWN
FIRE BEHAVIOR IN
CONIFER FORESTS**



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On the Cover:



Crowning associated with the major run of the Cottonville Fire in central Wisconsin at 5:11 p.m. CDT on May 5, 2005, in a red pine plantation. Photo taken by Mike Lehman, Wisconsin Department of Natural Resources.

The USDA Forest Service's Fire and Aviation Management Staff has adopted a logo reflecting three central principles of wildland fire management:

- **Innovation:** We will respect and value thinking minds, voices, and thoughts of those that challenge the status quo while focusing on the greater good.
- **Execution:** We will do what we say we will do. Achieving program objectives, improving diversity, and accomplishing targets are essential to our credibility.
- **Discipline:** What we do, we will do well. Fiscal, managerial, and operational discipline are at the core of our ability to fulfill our mission.



Firefighter and public safety is our first priority.

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by Tom Harbour
Director, Fire and Aviation Management
Forest Service

CROWN FIRE—A FASCINATING SIGHT

The National Wildfire Coordinating Group defines “crown fire” as “a fire that advances from top to top of trees or shrubs more or less independent of a surface fire. Crown fires are sometimes classed as running or dependent to distinguish the degree of independence from the surface fire.”

A crown fire, as defined by most people who see it happen for the first time: “*fascinating!*” Those who witness a crown fire for the first time often marvel in the dynamics of the fire as it moves very quickly from the top of one tree to another and then another. But as fascinating as it might be, it is important that you—as wildland firefighters and managers—recognize the different fire regimes and understand that while crown fires are natural in some fire regimes, in most they are not.

Crown fire is a normal disturbance process in some forest types and provides opportunities for species and wildlife habitat regeneration.

A crown fire, as defined by most people who see it happen for the first time: “*fascinating!*”

Wildfires can be caused by an accumulation of dead matter (leaves, twigs, and trees) that can create enough heat in some instances to spontaneously combust and ignite the surrounding area.

Other forest types are adapted to lower intensity, more frequent fire regimes. When planning fire and vegetation management activities, we must recognize these different fire regimes and associated fire dynamics. As professional wildland fire management leaders, we need to become fire ecologists, recognizing the fundamental fire ecology of each of these regimes and our need to coordinate our management activities so that they are in line with ecological processes.

We need to continue to work together with land management planners to ensure that these dynamics are recognized in the development of land management goals, objectives, and prescriptions. Aligning land management goals with local fire ecology will improve our success. Working together and changing the mindset to recognize that wildland fire management is a part of, and not separate from, the land management planning process is one of our biggest challenges.

This issue of *Fire Management Today* is dedicated to examining crown fires and is intended to increase awareness, to help you to better understand fire regimes and their relation to crown fires, and to enhance our ability to manage extreme fire behavior. This issue also contains discussion of some of the decision support tools now available and others being developed to assist fire, land, and resource managers now and in the future.

I'd like to thank the contributors to this issue for their work and efforts to increase fire regime awareness and keep our firefighters safe. ■

Working together and changing the mindset to recognize that wildland fire management is a part of, and not separate from, the land management planning process is one of our biggest challenges.

Preface

Mass media images of raging crown fires have affected how many people view their wildlands. Flames surge and leap dozens and even hundreds of feet into the air; planes zoom above the flames releasing streams of brightly colored retardant; and giant pyrocumulonimbus clouds tower over the landscape. No doubt, it's dramatic lead story material.

But, to many, and especially those in the wildland fire community, this is serious business. Tens of thousands of acres are severely burned in a single day; homes and lives are endangered; and ecosystems are changed dramatically for decades or longer. Crown fires demand our attention, and they demand serious study.

The Joint Fire Science Program is pleased to have contributed to the set of papers appearing in this special volume of *Fire Management Today*.

Today reporting the results of just such a serious study. The Joint Fire Science Program commissioned a thorough synthesis of knowledge and understanding regarding crown fire behavior in coniferous forests a few years ago, and now a summary of the results of that study is presented here in *Fire Management Today*.

We are all indebted to the authors of the papers included in this issue, especially to Dr. Marty Alexander (retired from the Canadian Forest Service and presently an Adjunct Professor at the University of Alberta), who led the project. These summary papers are the culmination of several years of work, and I believe you will find them of great value.

Please take a bit of time to give these papers a read. It is good to be armed with the best information available, especially on a serious subject like crown fires.

John Cissel
Program Director
Joint Fire Science Program



Martin E. Alexander
Issue Coordinator

Acknowledgments

This issue constitutes a contribution to Joint Fire Science Program Project JFSP 09-S-03-1. The original support of Mike Hilbruner, Dave Thomas, and Ralph Nelson Jr. (all Forest Service, retired) for the project is appreciated. Dr. Dave Peterson's (Forest Service, Pacific Northwest Research Station) role as a project co-principal investigator and Federal cooperator is duly acknowledged. Wesley Page (Utah State University), a former wildland firefighter and fuels specialist with the Forest Service, reviewed all of the articles in this special issue.

Contributors Wanted!

Fire Management Today is a source of information on all aspects of fire behavior and management at Federal, State, tribal, county, and local levels. Has there been a change in the way you work? New equipment or tools? New partnerships or programs? To keep up the communication, we need your fire-related articles and photographs! Feature articles should be up to about 2,000 words in length. We also need short items of up to 200 words. Subjects of articles published in *Fire Management Today* may include:

| | | |
|----------------------|--------------------------------------|--------------------------------|
| Aviation | Fire history | Planning (including budgeting) |
| Communication | Fire science | Preparedness |
| Cooperation | Fire use (including prescribed fire) | Prevention/Education |
| Ecosystem management | Fuels management | Safety |
| Equipment/Technology | Firefighting experiences | Suppression |
| Fire behavior | Incident management | Training |
| Fire ecology | Information management | Weather |
| Fire effects | (including systems) | Wildland-urban interface |
| | Personnel | |

INTRODUCTION TO THE SPECIAL ISSUE ON CROWN FIRE BEHAVIOR IN CONIFER FORESTS



Martin E. Alexander, Miguel G. Cruz, and Nicole M. Vaillant

Extrême fire behavior is defined by the National Wildfire Coordinating Group (from NWCG 2012) as:

“Extreme” implies a level of fire behavior characteristics that ordinarily precludes methods of direct control action. One or more of the following is usually involved: high rate of spread, prolific crowning and/or spotting, presence of fire whirls, strong convection column. Predictability is difficult because such fires often exercise some degree of influence on their environment and behave erratically, sometimes dangerously.

Prolific crowning is an element or characteristic of extreme fire behavior in conifer forests (figure 1). Joint Fire Science Program (JFSP) Project 09-S-03-1, “Crown Fire Behavior Characteristics and Prediction in Conifer Forests: A State-of-Knowledge Synthesis” (Alexander 2011, Alexander and others 2010), represents an outgrowth of JFSP’s interest in publishing a synthesis on the subject of extreme fire behavior and, more

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Figure 1.—One of the earliest line drawings of a running crown fire (from Davis 1959).

specifically, a critical review and analysis of the literature dealing with certain features of crown fires.

An abundant body of scientific knowledge concerned with the behavior of crown fires has accumulated over the past four decades or so. The aim of the project was to bring this work together in order to establish a solid foundation for our current understanding of crown fire behavior and to summarize it in a useful form for both fire managers and fire researchers.

The project focused on the onset of crowning; type of crown fires; and associated spread rate, fireline intensity and flame size, spotting, and elliptical fire area and perimeter growth (figure 2). In conifer forests, these fire characteristics are integral to the prediction of fire propagation across the landscape and the understanding of other aspects of extreme wildland fire behavior (for example, type of convection column development and various types of fire-induced vortices). While the project dealt primarily with the conifer forests

found in the United States and adjacent regions of Canada, relevant information from other parts of the world was sought out for its relevancy (Alexander and others 2012).

This special issue of *Fire Management Today* (FMT) contains eight articles highlighting the salient points gleaned from the resulting synthesis and supporting research articles—themselves a collaboration between JFSP Projects 09-2-01-11 and 11-1-4-16: “Extreme Fire Behavior State-of-the-Science Synthesis” (Alexander 2012, Werth and others 2011, 2014) and “The Influence of Fuel Moisture and Flammable Monoterpenes on the Combustibility of Conifer Fuels” (Jenkins and others 2012, Page and others in review)—augmented by three book chapters that comprise “Part Four—The Science and Art of Wildland Fire Behaviour Prediction” in Scott and others (2014). Some historical vignettes discovered during the literature search associated with the project have been incorporated within some of the papers of this special issue of FMT.

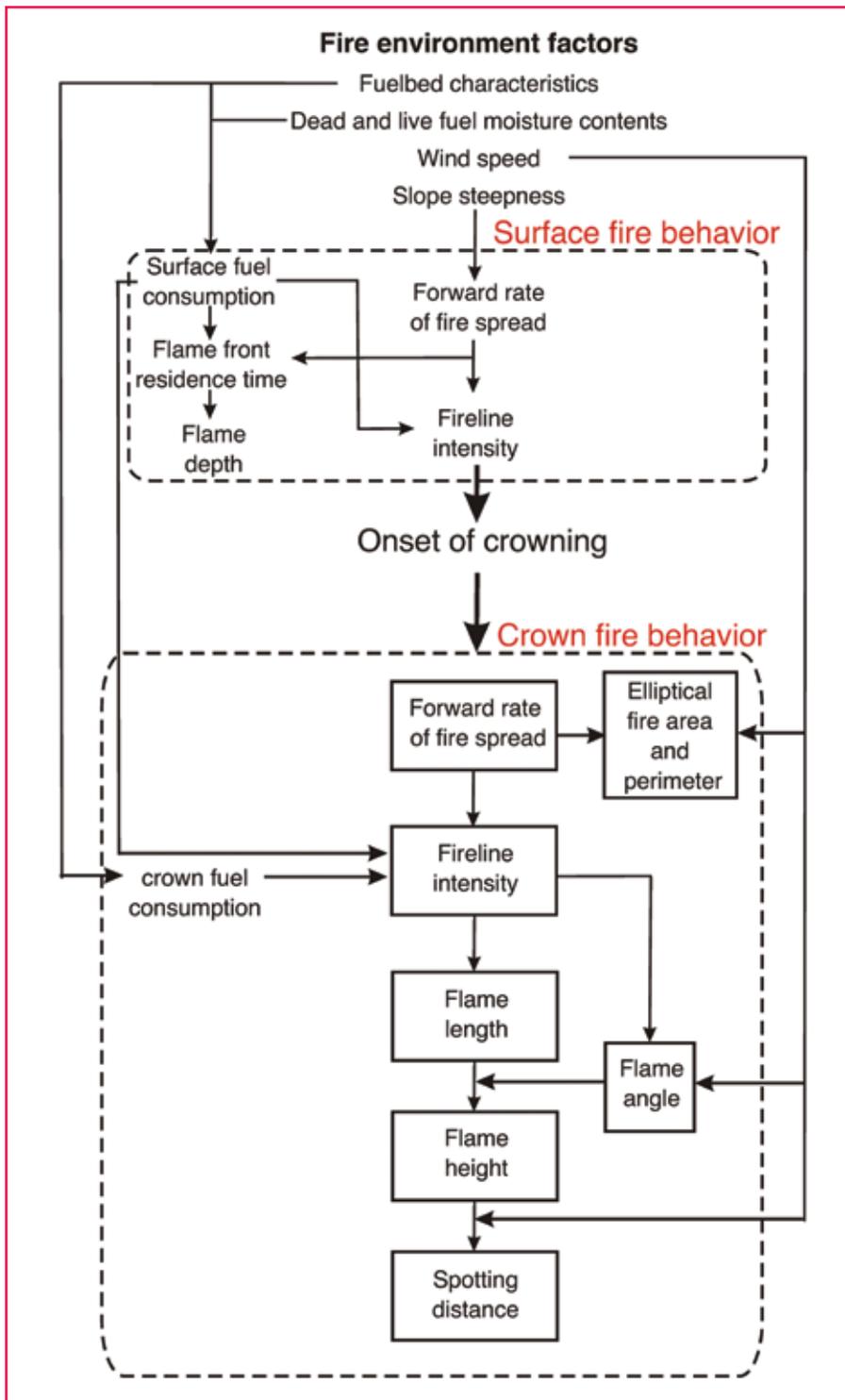


Figure 2.—Flow chart illustrating the linkages involved in the basic features of surface and crown fire behavior characteristics and the fire environment in conifer forests.

If You Want More Information on the Crown Fire Behavior Synthesis Project:

Select "Project Search" on the JFSP Web site (<http://www.firescience.gov/>) "Project Search" or visit <http://www.fs.fed.us/wwetac/projects/alexander.html>.

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THE GENERAL NATURE OF CROWN FIRES



Martin E. Alexander and Miguel G. Cruz

In conifer forests, three broad types of fire are commonly recognized on the basis of the fuel stratum or strata controlling their propagation:

- Ground or subsurface fire,
- Surface fire, and
- Crown fire.

Ground or subsurface fires burn very slowly in the duff layer with no visible flame and sometimes with only the occasional wisp of smoke. Surface fires spread in the litter and dead-down woody fuel layer of a stand in either the heading direction with the wind and/or upslope, or as backing fires advancing into the wind and/or downslope.

Crown fires are dependent on a surface fire and, in some instances, ladder or bridge fuels for both its initial onset and capacity for maintaining flames in the crown space of a conifer forest stand. Thus, a crown fire advances through both the surface and tree canopy fuel layers with the surface and crown fire phases more or less linked together as a single unit. Thus, the term “crowning” refers to both the fire’s ascension into the crowns of trees and the spread from tree to tree.

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According to Davis, “In actual fire situations, these three kinds of fire may occur simultaneously and in all kinds of combinations. Surface fires are by far the most common, and nearly all fires start as such. A surface fire may spread into the crowns and develop into a sweeping crown fire. A crown fire may drop to the ground and become a surface fire. Similarly, a surface fire may develop into a stubborn ground fire that may plague control forces for days or weeks. On a hot, dry, and windy afternoon, a rather innocuous-looking ground fire may be fanned into surface or crown fire” (1959).

The Power and Significance of Crown Fires

Crown fires in conifer forests constitute one of nature’s most spectacular phenomena. The power exhibited by crown fires, including the spawning of tornadic-like activity, can leave one awestruck—as it did pioneer forest fire researcher Harry T. Gisborne (see the sidebar). Crown fires can, for a number of reasons, be dangerous for firefighters to attempt to control by direct attack. They also pose a safety threat to members of the general public that live, work, and recreate in crown fire-prone environments.



Active crowning associated with the Jackpine Fire in the Willmore Wilderness Park, Alberta, Canada, at 4:29 p.m. MDT on July 4, 2006. Photo taken by Emile Desnoyers, Alberta Environment and Sustainable Resource Development.

Until there is a major, favorable change in the prevailing environmental conditions (fuels, weather, and/or topography), there is little that can be done to contain the headlong rush of a high-intensity crown fire—at least by conventional means of suppression, including attack by aircraft. This is due to the crown fire’s rate of spread, the fierce thermal radiation emitted by the “wall of flame” front, and the spotting activity downwind of the main advancing front. Crown fires are thus capable of burning large tracts of forested landscape, seriously impacting environmental and ecosystem resources, damaging and destroying values at risk in the wildland-urban interface zone, and increasing fire suppression expenditures.

Types of Crown Fires

The term “crown fire” has appeared in the forestry and ecological literature since at least the 1880s. Eventually, two broad types or classes of crown fire—“dependent crown fire” and “running crown fire”—became recognized by the late 1930s to distinguish the degree of dependence upon the supporting surface fire. A dependent crown fire depends upon the heat generated by the surface fire for its spread whereas a running crown fire is one that generates enough heat for crown-to-crown spread.

Other terms have come to describe crown fires: “fully developed” crown fire (Luke and McArthur 1978), “wind-driven” and “plume-dominated” crown fires (Rothermel 1991), and “intermittent” and “continuous” crown fires (Forestry Canada Fire Danger Group 1992). Van Wagner’s (1977) crown fire classifi-



Post-burn mosaic pattern in the Bunsen Peak area of Yellowstone National Park associated with the occurrence of the North Fork Fire during the 1988 fire season, illustrating various types of fire activity. This includes: (i) no fire, ground fire, and low-intensity surface fire (green crowns); (ii) high-intensity surface fire and passive crown fire (red, scorched crowns); and active crown fire (black, flame defoliated crowns). Photo by Jim Peaco, National Park Service, courtesy of the Yellowstone Digital Slide File.

cation is the most widely accepted. He proposed that three kinds or classes of crown fire could be described according to their degree of dependence on the surface phase of fire spread using several semi-mathematical statements:

- Passive crown fire,
- Active crown fire, and
- Independent crown fire.

The third kind or class was regarded as a rare and short-lived occurrence (Van Wagner 1993).

Generally, all fires classed as crown fires contain areas of ground fire and low- to high-intensity surface fires as well. In dense, conifer-dominated forested landscapes, this complex mosaic pattern is the result of short-term variations in wind speed and direction interacting with stand structure, surface fuel characteristics, and topography (Alvarez and others 2013). Van Wagner (1977) regarded this type of crown fire behavior as “intermittent active crowning.”

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Harry T. Gisborne's Account of the 1929 Half-Moon Fire "Explosion"[†]

Newspaper accounts of large forest fires in the northern Rocky Mountain region frequently refer to "runs," "blow-ups," and occasionally to "explosions" of the fire.

"When Montana's largest human-caused fire, the 90,000-acre [36,425 ha] Half-Moon conflagration, ran this summer [1929] from Teakettle Mountain to Belton and Glacier Park Headquarters in 1 afternoon it left a trail of desolation which ruined that 12-mile [19 km] auto drive for many, many years.

"At the Desert Mountain forest-fire lookout station, 4 miles [6.5 km] south of Belton and 5,000 feet [1,525 m] above it, the man on duty made fast time down the 9-mile [14.5 km] trail to Coram Ranger Station when the head of this fire came roaring toward his mountain. But the natural wind channel, formed by the gorge of the Middle Fork of the Flathead River, drew the center of devastation past him temporarily. Two days later, on August 23, 1929, we went back to the top of Desert to obtain measurements of atmospheric temperature, humidity, and wind, and to note for comparison the behavior of the fire in different timber types on different slopes and exposures according to the prevailing weather.

"We arrived in the lookout station about noon and after making a first series of weather measurements. I went north the half mile along the ridge top to Belton

Point, a secondary observation station.

"At the time the southern flank of the fire was still over a mile [1.6 km] from the base of the steep north end of the mountain. Perhaps 6 miles [10 km] of front were visible, the rest hidden by soft swirls of big columns of smoke. Although the front below me was beginning to boil actively in the green timber, as a result of rising temperature and wind and decreasing afternoon humidity, it was not yet crowning extensively. And with the light wind coming from the southwest, diagonally opposite the advance toward the south, I thought it was safe to go down to the spring, some 800 feet [245 m] in elevation and 13 switchbacks by trail, below Belton Point and on its eastern slope."

"The trip to the spring and back to the lookout station, with a 5-gallon [19 l] back-pack, was completed just in time for the 4 o'clock weather measurements. It seemed preferable, however, to make these on Belton Point closer to the fire and where the front, which was now very active, could be seen more extensively than from the main station. This was a sad decision, because it resulted in no measurements whatever.

"The lookout, Mr. Tunnell, who had been cleaning up the cabin while I went for water, decided to go with me to Belton Point. As we walked toward it, smoke was boiling up from the north end of the mountain in a tremendous pillar towering ... above our 7,400-foot [2,255 m] station. Just as when one

looks up from sidewalk at the base of a sky-scraper the top is out of view, so the top of this column of smoke was hidden by its sides, even though we were over half a mile [0.8 km] from its base. For some unknown reason, the customary roar of such rapidly rising masses of smoke, gas, and flame was not present in this case, nor did I notice it later when the mile [1.6 km] wide whirling "explosion" developed and swept in under us. It was obvious, nevertheless, that the fire front that had been over a mile from the base of the mountain an hour ago was now going to reach Belton Point before we could, or at least before we would.

"Like all truly massive movements the great pillar of smoke belching from the north face of the mountain seemed to move slowly. Black bodies of unburned gases would push their fungoid heads to the surface of the column, change to the orange of flame as they reached oxygen, and then to the dusty gray of smoke. Huge bulges would grow slowly on the side of the column obliterating other protuberances and being in turn engulfed. We could see beautifully, as the atmosphere between the fire and us was kept clear by the light southwesterly wind. There seemed to be no danger as the mountain of smoke leaned appreciably with this breeze, and leaned away from us. We went forward about 200 yards [180 m].

"Such a spectacle, even as it enlarged one's heart enough to interfere with normal breathing, made us wish for the presence of others to enjoy the thrill. We

[†]Adapted from Gisborne (1929)

stopped to take two pictures, one of the soft and apparently slowly boiling smoke column to the north, and one to the northeast out across the 2-mile [3.2 km]-wide canyon. Down there lay the valley in the shadow of death, but although even the poor photograph portrays it, we did not realize what was to happen in the next few minutes.

“Even as I snapped these two photographs, we noticed that the wind velocity was increasing. One glance at the boiling inferno north of us, and we saw the reason. The southwest wind, sweeping gently as it was around northwest shoulder of Desert Mountain, was striking the periphery of a rising mass of

hot gas and smoke. The result was the being of a whirling, clockwise motion, with the deep canyon east of us acting to draw the center of suction into it.

“Suddenly, yet it seemed slowly—the movement was so massive, the curtain of smoke across the mouth of the canyon bulged at about our level. The bulge moved south, up the canyon, turned toward the southwest and up the slope towards us.

“Most of this we saw over our shoulders as we sprinted south along the open ridge-top trail to the lookout cabin. As we dashed in the door to snatch our packsacks, we saw a sec-

ond whirl developing. As we came out the door, hurriedly adjusting our shoulder snaps, the new revolution swept majestically up the creek, up the slope under the lookout cabin—but a full quarter mile [0.5 km] below us, turned west, northwest, and north, and obliterated the spot from which we had taken our pictures.

“Then came the finale, the explosion, the display that should terminate any really spectacular show. The suction of this rising mass of heat drew the air across our ridge with a velocity that bounced me up against the lookout house as I stood there gaping. About 2 square miles [5.2 km²] of surface area, over 1,300 acres [525 ha], were devastated by these two whirls in a period of possibly 1 or 2 minutes.

“Ordinarily, the front of a forest fire advances like troops in skirmish formation, pushing ahead faster here, slower there, according to the timber type and fuels, but maintaining a practically unbroken front. Even when topography, fuels, and weather result in a crown fire, the sheet of flames leaps from tree crown to the next, changing green forest to black ruins at a relatively slow rate, from one-half to 1 mile an hour [0.8 to 1.6 km/h], according to two measured runs on the Sullivan creek fire. “Blow-ups” begin when such “runs” commence to throw spots of fire ahead of the advancing front, the spots burning back to swell the main front and thereby adding appreciably to the momentum of the rising mass of heat. Men have been able to race out to safety from in front of many ordinary runs and crown fires. Some men have escaped and some have been trapped by blow-ups.”



The first of two photographs taken of the Half-Moon Fire by H.T. Gisborne from between Belton Point and Desert Mountain Lookout during the late afternoon of August 23, 1929. From the Harry Thomas Gisborne Papers, Archives & Special Collections, Mansfield Library, University of Montana, Missoula, MT.

CANOPY-FUEL CHARACTERISTICS OF CONIFER FORESTS



Miguel G. Cruz and Martin E. Alexander

Conifer forest stands are comprised of living and dead biomass in four separate fuel strata according to their vertical distribution and effects on fire behavior (see figure 1):

- Ground fuels—principally the duff layer of the forest floor;
- Surface fuels—the litter layer of the forest floor, mosses and lichens, dead down woody debris, herbaceous vegetation, and short to medium-height shrubs;
- Ladder or bridge fuels—tall shrubs, understory conifer trees and loose bark, lichens, and dead branches on tree boles located in the space between the top of the surface fuel stratum and the bottom of the canopy-fuel stratum;
- Canopy fuels—chiefly the live and dead needle foliage, twigs, small branchwood, and aerial lichens and mosses associated with the overstory tree cover.

It is generally accepted that a distinct separation exists between surface fuels and canopy fuels: an open trunk space in which ladder or bridge fuels vary widely in their abundance. Collectively, the four

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strata constitute a forest fuel complex. An indication of the variation in canopy-fuel weight by height above ground is given in figure 2.

Many aspects of crown fire behavior have been found to be strongly

linked to extrinsic canopy-fuel characteristics:

- Canopy-base height,
- Canopy-fuel load,
- Canopy-bulk density, and
- Foliar moisture content.

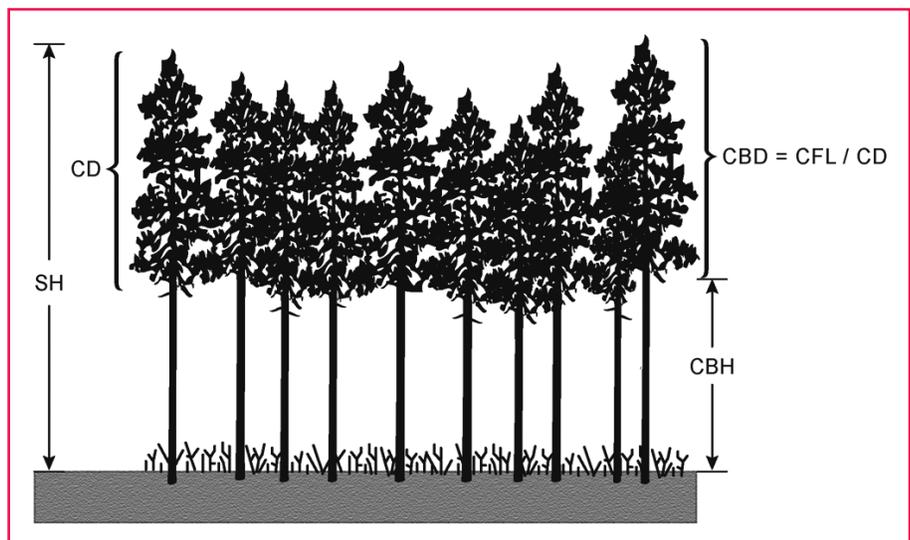


Figure 1.—Profile of a stylized conifer forest stand illustrating several stand and canopy-fuel characteristics: stand height (SH), crown depth (CD), canopy-base height (CBH), canopy-fuel load (CFL), and canopy-bulk density (CBD).

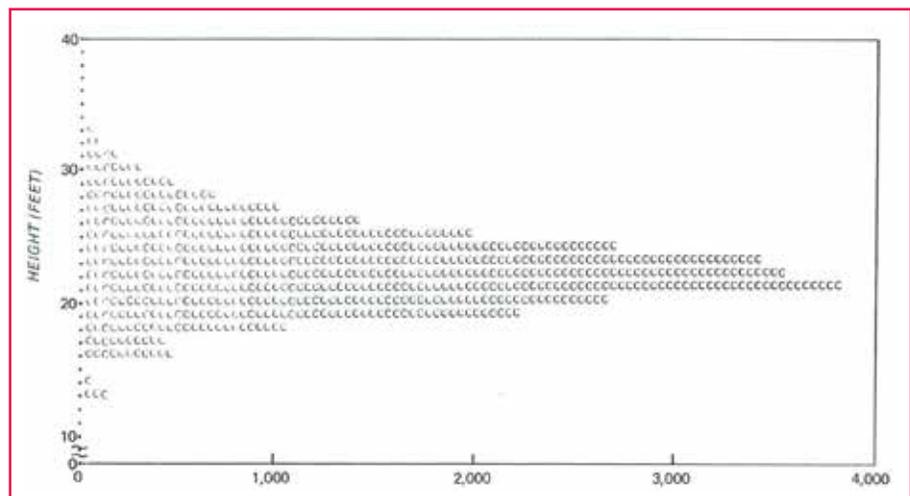


Figure 2.—Graph of canopy-fuel weight with height above ground in a 32-year-old red pine plantation (from Sando and Wick 1972).

One of the main problems in determining the canopy-base height is the lack of a universally accepted definition for the lower limit of the canopy-fuel stratum.

Various intrinsic canopy-fuel characteristics (for example: the variation in foliar heat content) have yet to be seen as major factors in determining any particular element of crown fire behavior.

Canopy-Base Height

One of the main problems in determining canopy-base height (CBH) is the lack of a universally accepted definition for the lower limit of the canopy-fuel stratum (Fernández-Alonso and others 2013, Cruz and others 2004). Van Wagner (1977) defined CBH as the average height from the ground surface to the lower live crown base of the overstory trees in a conifer forest stand. Cruz and others (2003, 2010) adopted the same definition in relating tree and stand characteristics to the estimation of CBH (figure 3) in which the stand height (SH) represents the average of all trees in the stand rather than the dominant or top tree height (see also Cruz and Alexander 2012).

Canopy-Fuel Load

Canopy-fuel load (CFL) represents the quantity of fuel per unit area that would typically be consumed in the overstory trees of a conifer forest stand during the crown-ing process—in other words, the “available” canopy fuel. As Van Wagner (1977) notes: “Visual expe-

rience suggests that the principal crown fuel consumed is the live foliage and that little else burns except in unusually intense fires.” Admittedly, smaller quantities of

both dead and live woody material, bark flakes, and lichens and mosses may also be combusted. The CFL is a product of stand structure characteristics (figure 4).

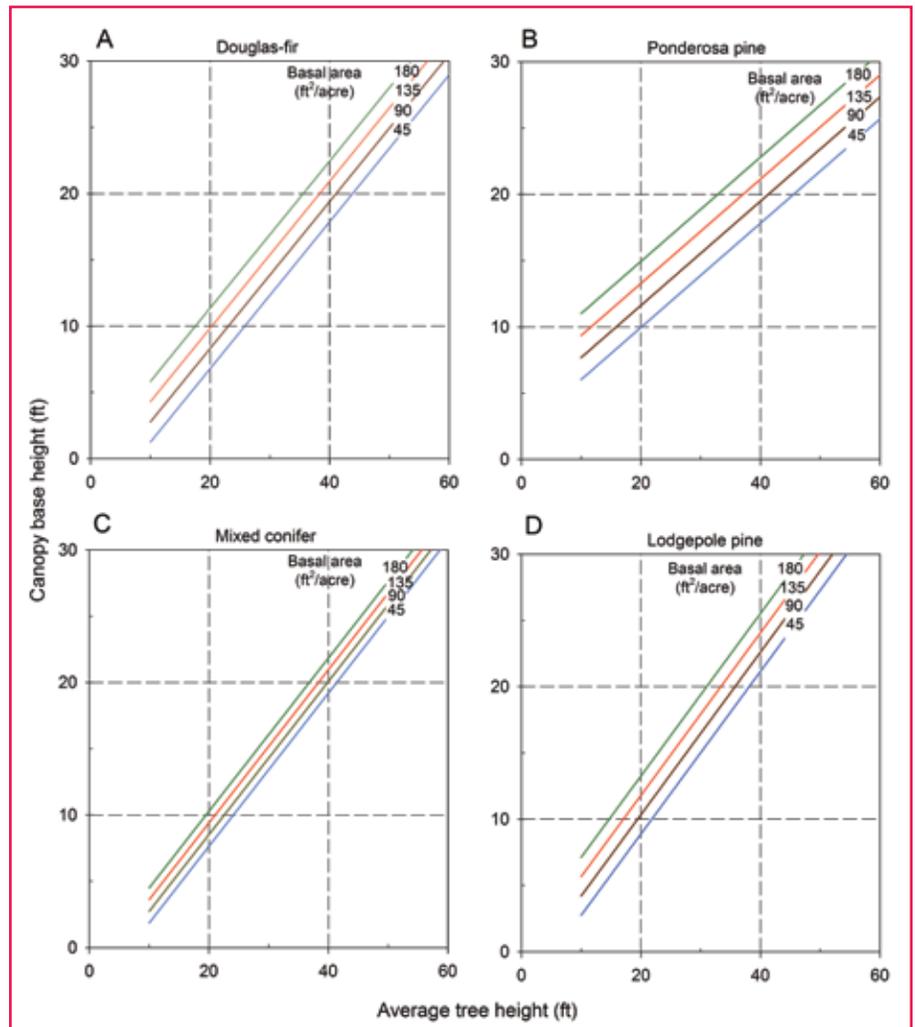


Figure 3.—Canopy-base height of four western U.S. conifer forest fuel types as a function of average stand height and basal area (from Cruz and others 2003).

The Fuel Strata Gap Concept

Fuel strata gap (FSG) is defined as the distance from the lower limit of the crown fuel stratum that can sustain vertical fire propagation and the top of the surface fuel layer. FSG is equivalent to canopy-base height (CBH) in the absence of appreciable ladder fuels when the surface fuel height is minimal. The FSG concept was introduced by Cruz and others (2004) to overcome the issue of the application of the CBH term to two distinct physical situations: (1) the silvicultural definition of only live foliage and (2) the fire modeling definition incorporating ladder fuels (Scott and Reinhardt 2001).

Canopy-Bulk Density

Canopy-bulk density (CBD) represents the amount of available crown fuel within a unit volume of the overstory trees in a conifer forest stand. The CBD is computed by dividing the CFL by the canopy depth (CD). The CD in turn is the stand height (SH) minus the CBH where the SH is the average height of all overstory trees in the stand. Thus, CBD is a reflection of stand structure characteristics (figure 5).

Foliar Moisture Content

Foliar moisture content (FMC) represents a weighted average of composite moisture content for the various needle ages found within the crowns of the trees in a conifer stand; this can also include other live and dead fuels (for example, lichens, mosses, and twigs). Upon emergence in the spring, new needles have very high levels of FMC (for example: 250–300 percent oven-dry weight basis), steadily decrease in FMC to approximately

Sampling of coniferous tree foliage has revealed a common pattern during the fire season: a period of relatively low foliar moisture content values in the spring and early summer commonly referred to as the “spring dip.”

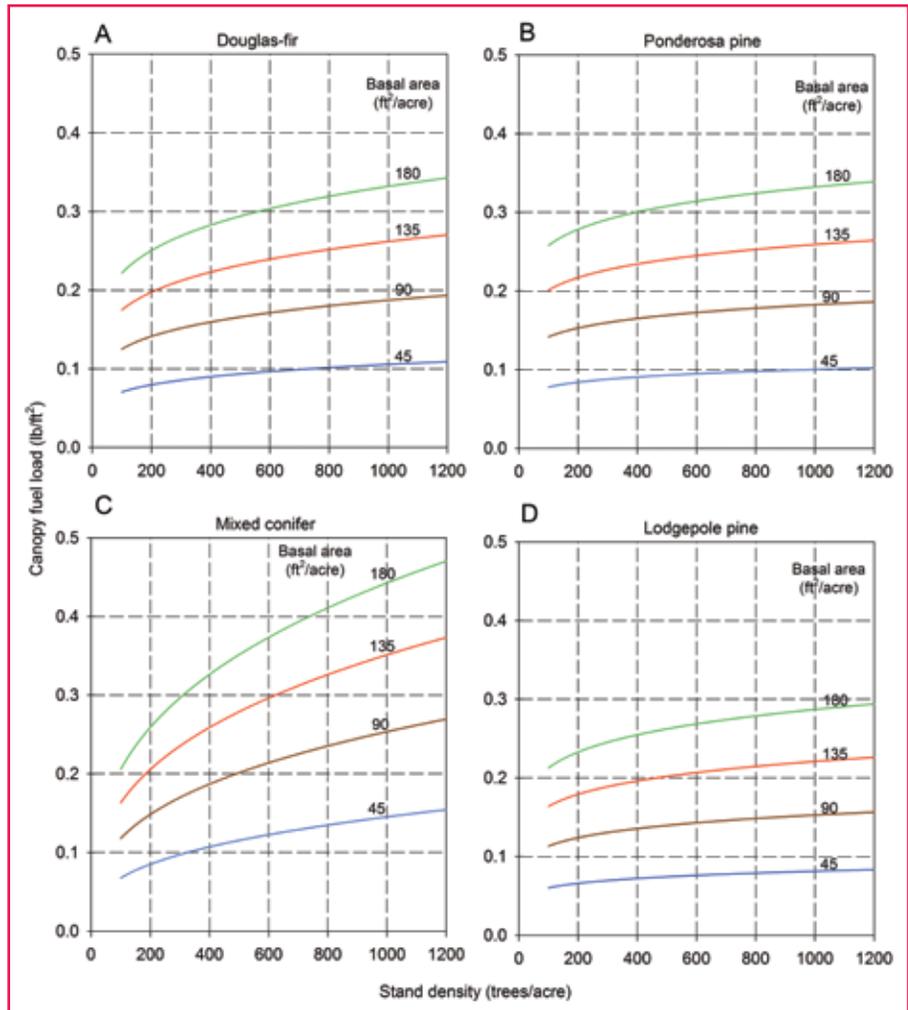


Figure 4.—Canopy-fuel load of four U.S. Interior West conifer forest fuel types as a function of stand density and basal area (from Cruz and others 2003).

Take Note!

Various authors (for example: Scott and Reinhardt 2001, Reinhardt and others 2006) have come to define canopy-bulk density (CBD) as the maximum 10-foot (3-m) running mean of a vertical canopy-fuel profile and canopy-base height (CBH) as the lowest point in the profile, where CBD is ≥ 0.000749 pounds per cubic foot (0.012 kg/m^3). These authors also defined the canopy-fuel load (CFL) as the needle foliage plus the <0.762 inches (0.3 cm) diameter live and <1.52 inches (0.6 cm) diameter

dead twig material. These definitions of CBH, CFL, and CBD are used in various fire behavior modeling systems, such as the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Rebain 2010) and Fuel Management Analyst Plus (Maples) (Carlton 2005). Strictly speaking, these adjustments or modifications are not compatible with Van Wagner’s (1977) semi-empirical models for crown fire initiation and propagation (Cruz and Alexander 2012).

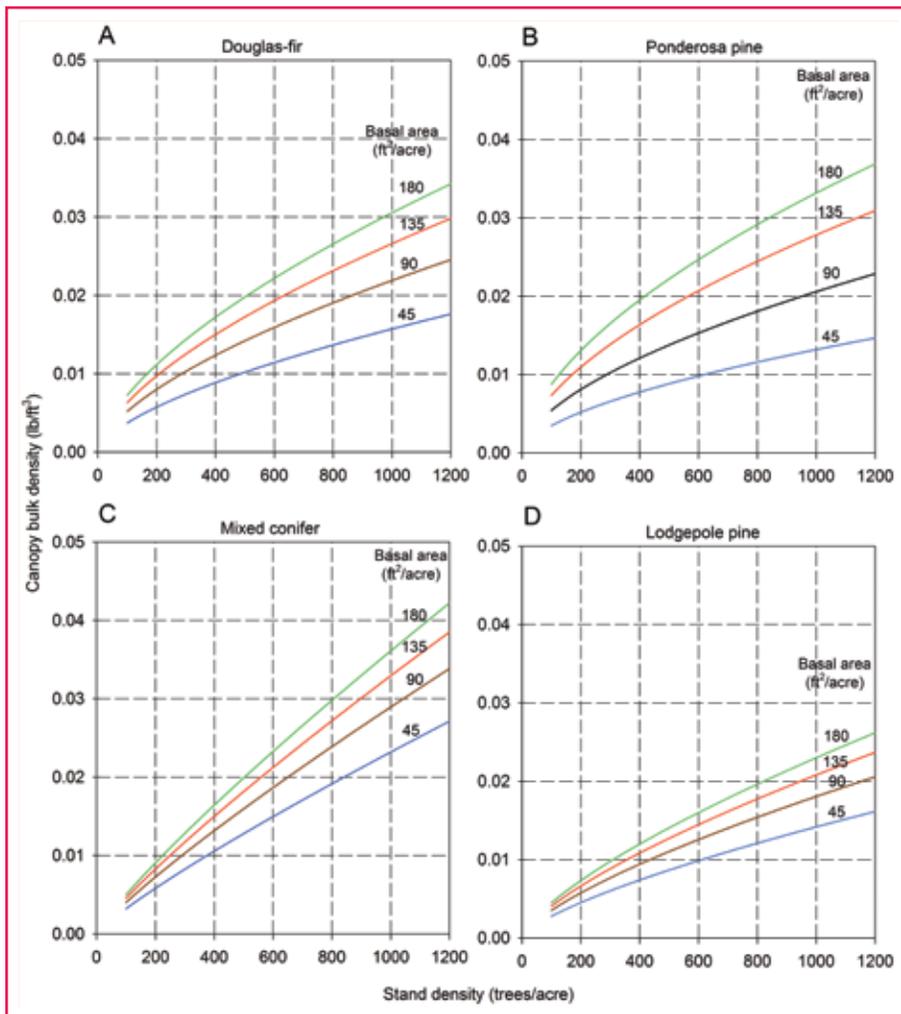


Figure 5.—Canopy-bulk density of four western U.S. conifer forest fuel types as a function of stand density and basal area (from Cruz and others 2003).

The Canopy-Fuel Characteristics Calculator

The regression equations developed Cruz (2003) for estimating the canopy-base height, bulk density, and fuel load in ponderosa pine, lodgepole pine, Douglas-fir, and mixed conifer forest stand types—based on three stand characteristics (average height, basal area, and stand density)—have been programmed into a Microsoft Excel spreadsheet (Alexander and Cruz 2010). The software is available for downloading the spreadsheet at <http://www.frames.gov/partner-sites/applied-fire-behavior/cfis>.

125–140 percent by the end of the first growing season (figure 6), and then decrease in FMC very gradually in the years that follow.

Repeated FMC sampling of coniferous tree foliage at several locations across Canada and in adjacent areas of the northern continental United States and Alaska has revealed a common pattern during the fire season: namely, a period of relatively low FMC values in the spring and early summer before the emergence of new needles (Alexander 2010). This phenomenon is commonly referred to as the “spring dip.”

Field Estimation

Direct measurement of canopy-fuel characteristics can be an expensive and time-consuming activity. While a number of indirect methods have been tried for estimating CBD, for example, none have proven to be adequate (Alexander and Cruz 2014).

Tables have been constructed for use in making quick and reliable estimates of CBH, CFL, and CBD from visual observations or field measurements of stand height, basal area, and stand density for several different Interior West conifer forest stand types of the United States (Alexander and Cruz 2014). The construction of the tables is based on regression equations previously developed by Cruz and others (2003) and evaluated by Cruz and Alexander (2012). The approach used could no doubt be extended to other conifer forest types.

Several FMC studies undertaken in the United States and Canada (figure 6) were summarized by Keyes (2006). FMC can be also estimated by direct measurement (Jolly and Hadlow 2012, Norum and Miller 1984) or indirectly using empirical models based on calendar date and other environmental factors (Alexander 2010). One example of the latter approach is the *Calculator of Foliar Moisture Content in Pitch Pine* (<http://www.umass.edu/nebarrensfuels/ma_barrens/montague/#needles>).

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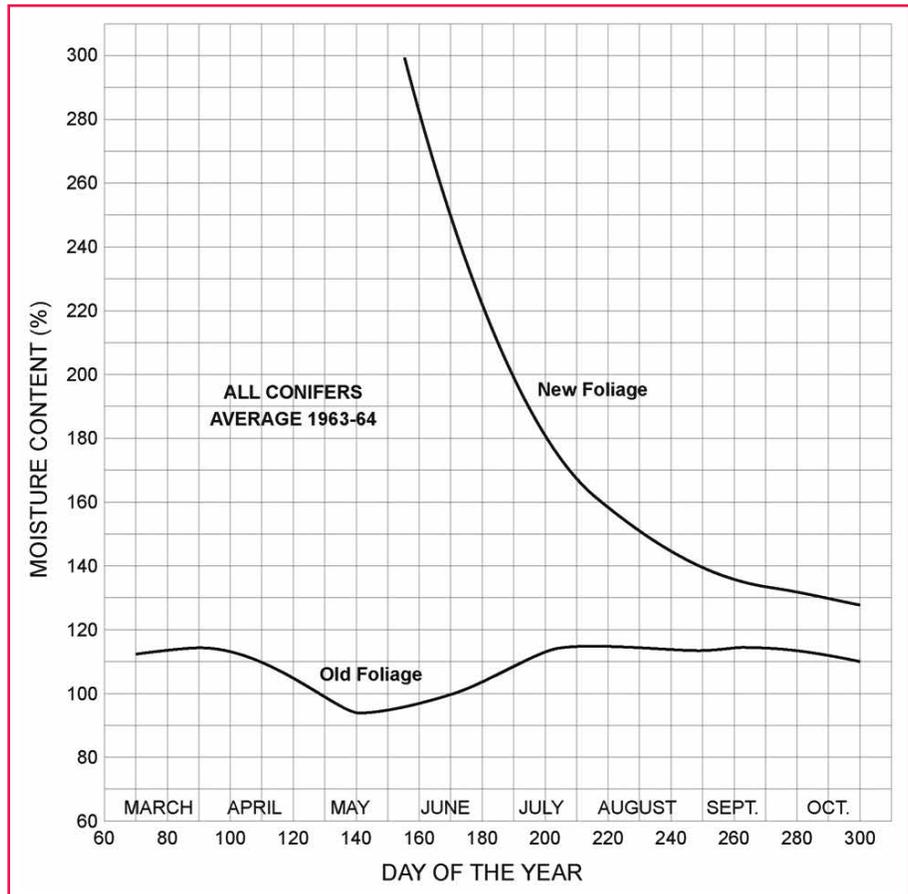


Figure 6.—The average seasonal trends in the moisture content of old and new needle foliage for conifer tree species sampled at the Petawawa Forest Experiment Station near Chalk River, Ontario, Canada, over the course of 2 years (from Van Wagner 1977).

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THE START, PROPAGATION, AND SPREAD RATE OF CROWN FIRES



Miguel G. Cruz and Martin E. Alexander

In many respects, the most significant issue with regards to the prediction of crown fire behavior is first determining whether a surface fire will develop into a crown fire (that is, identifying the conditions favorable to the initiation or onset of crowning). The next concern is whether the crown fire can continue to perpetuate itself and, if so, what the rate of spread will be.

Crown Fire Initiation

For a crown fire to start, a surface fire of sufficient intensity is first necessary. The distance between the heat source at the ground surface and the canopy-fuel layer will determine how much of the surface fire's energy is dissipated before reaching the fuels at the base of the canopy. The higher the canopy base, the lower the chance of crowning. Furthermore, if the moisture content of the canopy fuels is high, greater amounts of energy are required to raise the canopy tree foliage to ignition temperature.

Several empirical and semiphysical models have been developed over the past 35 years for predicting the initiation or onset of crowning. The simplest explanation of the general processes involved is offered by Van Wagner (1977a). Using physical rea-

soning and empirical observation, Van Wagner proposed that vertical fire spread (that is, the initiation of crowning) would begin to occur in a conifer forest stand when the surface fire's intensity (SFI) or energy release rate (taken from Byram 1959) attains or exceeds a certain critical value (CSFI). The former quantity (referred to as "fireline intensity") is equal to the product of the heat yield of the burned fuel, quantity of fuel consumed, and the rate of fire spread (figure 1A); flame size (figure 1B) is the main visual manifestation of fireline intensity (Alexander and Cruz 2012a, 2012b).

According to Van Wagner's (1977a) theory of crown fire initiation, the CSFI is dictated by the foliar

moisture content and the canopy-base height (figure 2). If the SFI is greater than or equal to the CSFI, some form of crowning is presumed to be possible, but if the SFI is less than the CSFI value, a surface fire is expected to remain so. Nevertheless, crown scorch may occur, depending on the canopy-base height (figure 1B).

From figure 2A, it should be clear that the higher the canopy-base height and/or foliar moisture content, the more intense a surface fire must be to cause crowning. It is worth noting that the flames of a surface fire don't necessarily have to reach or extend into the lower tree crowns to initiate crowning (figure 2B).

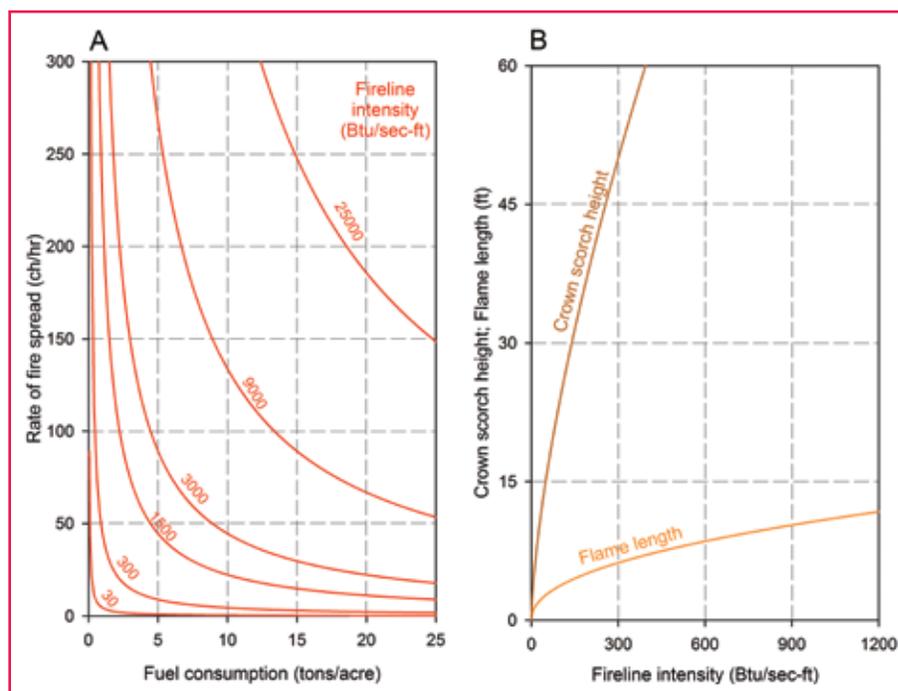


Figure 1.—Graphical representation of (A) fireline intensity as a function of rate of fire spread and fuel consumption assuming a net low heat of combustion of 7740 British thermal units/lb (18 000 kJ/kg) (adapted from Alexander and Cruz 2012c) and (B) Byram's (1959) flame length-fireline intensity, y and Van Wagner's (1973) crown scorch height-fireline intensity relationships.

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Crown Fire Propagation

Assuming that a given surface fire has sufficient intensity to initiate and sustain crown combustion from below, can a solid flame front develop and maintain itself within the canopy-fuel layer in order for horizontal crown fire spread to occur? Van Wagner (1977a) theorized that a minimum flow of fuel into the flaming zone of a crown fire is required for combustion of the canopy-fuel layer to continue.

This minimum flow of fuel being volatilized is a direct function of the speed of the fire and the fuel available per unit volume—the canopy-bulk density. For any given forest stand structure, there will be a critical or minimum threshold in rate of fire spread that will allow active crowning to be sustained relative to the canopy-bulk density (figure 3).

Active crowning is presumably not possible if a fire does not spread rapidly enough following initial crown combustion. Thus, if a fire's actual spread rate after the initial onset of crowning—a function largely of the prevailing wind speed and/or slope—is less than the critical rate of fire spread needed for active crowning, a passive crown fire is expected to occur (figure 3).

Any changes in forest stand structure that reduce the canopy-bulk density results in an increase in the critical rate of fire spread needed for active crowning. This is to say that, for lower canopy-bulk densities, more severe burning conditions (for example, higher wind speed and lower dead fuel moisture content) are required to maintain a self-sustaining active crown fire. High canopy-bulk densities are associated with dense stands, and low values are associated with open stands.

The validity of Van Wagner's (1977a) relation for active crown fire propagation has since been confirmed on the basis of a relatively large dataset of experimental crown fires (Cruz and Alexander

2010). Furthermore, canopy-bulk density levels of around 0.003 pounds/cubic foot (0.05 kg/m^3) and 0.006 pounds/cubic foot (0.1 kg/m^3), corresponding to critical minimum spread rates of 180

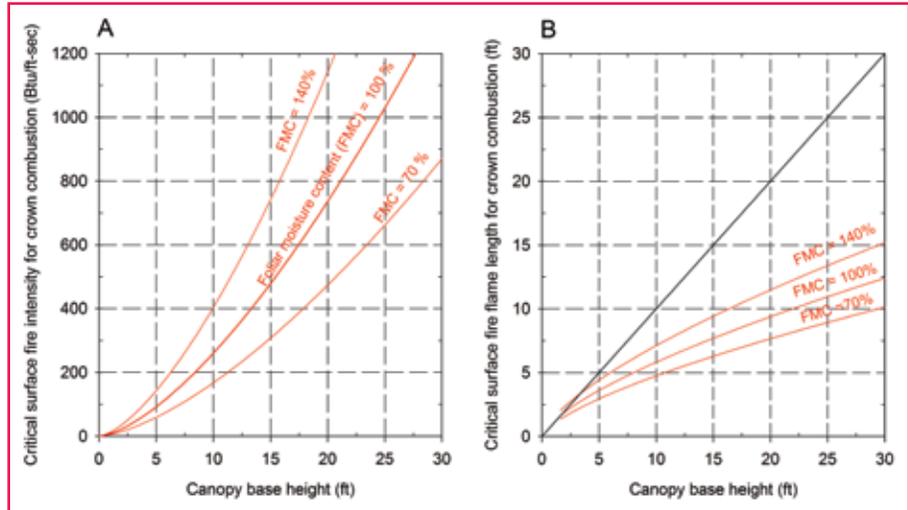


Figure 2.—Graphical representations of (A) critical surface fire intensity for crown combustion in a conifer forest stand as a function of canopy-base height and foliar moisture content according to Van Wagner (1977a) and (B) the critical surface fire flame length for crown combustion in a conifer forest stand as a function of canopy-base height according to the flame length–fireline intensity model of Byram (1959); the diagonal line represents the boundary of exact agreement between flame length or height and canopy-base height.

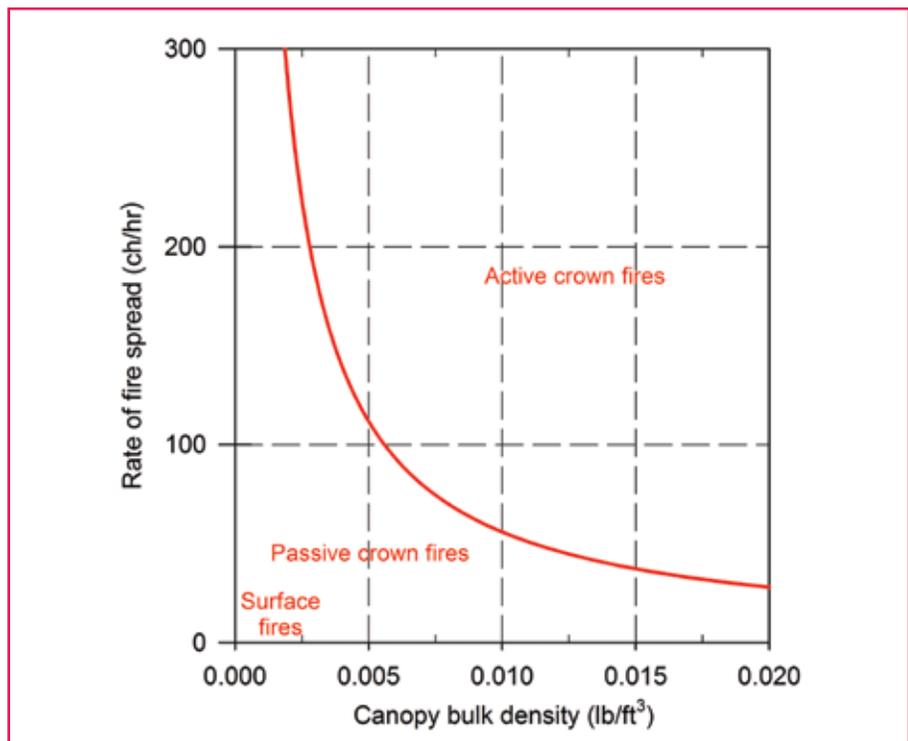


Figure 3.—Critical minimum spread rate for active crowning in a conifer forest stand as a function of canopy-bulk density according to Van Wagner (1977a).

to 90 chains/hour (60 and 30 m/min), respectively, have come to represent thresholds for passive and active crown fire development.

A passive crown fire is not a benevolent form of crown fire activity. Passive crown fires can spread at very high rates and release large amounts of energy in a very short period of time, thus creating hazardous and potentially life-threatening situations. This typically occurs in fires spreading through open stands with a low canopy-bulk density or closed-canopied stands exhibiting a very high canopy-base height; in such a case, spread rates might reach as high as 75 chains/hour (25 m/min) with associated fireline intensities of 2,900 British thermal units/second-foot (10,000 kW/m) and flame lengths of around 18 feet (5.5 m).

According to Van Wagner's (1977a) theories of crown fire initiation and propagation, it can now be seen why some conifer fuel complexes are far more prone to or have a greater propensity for crowning than others simply because of their intrinsic fuel properties. For example, many of the black spruce forest types found in Alaska and the Lake States, as well as Canada, are known to be notoriously flammable. This occurs as a result of a combination of low canopy-base height typical of this tree species, the abundance of ladder or bridge fuels (that is, bark flakes, lichens, and dead branches on the lower tree boles), low foliar moisture content levels, moderately high canopy-bulk densities, and potentially other fuel properties (for example, cones as firebrand material and high live-to-dead ratios of available fuel within the tree crowns).

Crown Fire Rate of Spread

Surface fires spreading beneath conifer forest canopies seldom exceed 15 to 30 chains/hour (5 to 10 m/min) without the onset of crowning in some form or another. General observations of wildfires and documentation of experimental crown fires indicate that a rather abrupt transition between surface and crown fire spread regimes (in both directions) is far more commonplace than a gradual transition. With the onset of crowning, a fire typically doubles or triples its spread rate in comparison to its previous state on the ground surface (figure 4). This sudden jump in the fire's rate of spread occurs as a result of the fact that the wind speeds just above the tree canopy are about 2.5 to 6 times higher than understory winds, there is an increased efficiency of heat transfer

into a tall and porous fuel layer, and there is a possible increase in spotting density just beyond the fire's leading edge.

Once crowning has commenced, a fire's forward rate of spread on level terrain is influenced largely by wind velocity (figure 4) and, to a lesser extent, by physical fuel properties. If ground and surface fuels are dry and plentiful and ladder fuels or bridge fuels are abundant, crown fires can still propagate in closed-canopied forests even if winds are not especially strong, although spread rates may not be particularly high.

Van Wagner (1998) also believed that the natural variation in foliar moisture content would presumably have an effect on the rate of spread of a crown fire in addition to being a factor influencing the onset of crowning in conifer forest

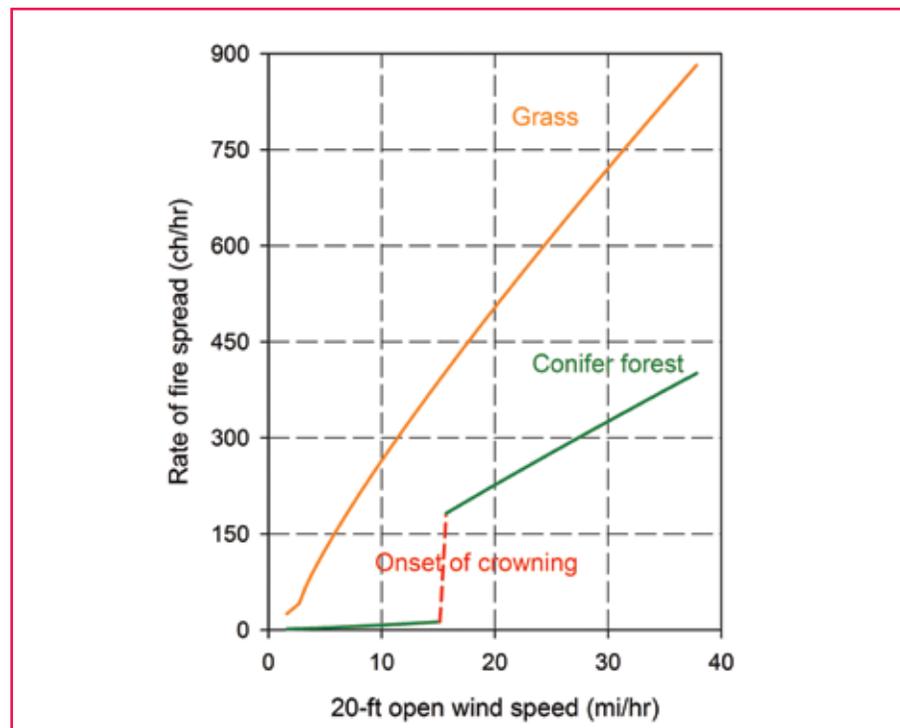


Figure 4.—The variation in rate of fire spread in relation to wind speed for a conifer forest stand compared to a grassland fuel complex (after Alexander and Cruz 2011). The “kink” in the curve associated with the conifer forest represents the point of surface-to-crown fire transition.

stands. Alexander and Cruz (2013) reviewed the literature related to this topic and concluded that the evidence from outdoor experimental fires did not necessarily support this conclusion.

Continuous active crowning generally takes place at spread rates between about 45 and 90 chains/hour (15 and 30 m/min). A “mile an hour”—80 chains/hour (1.6 km/hr or 27 m/min)—has been suggested by some authors as a rough rule of thumb for crown fire rate of spread (see Van Wagner 1968). This appears to be somewhat of an underestimate according to the work of Alexander and Cruz (2006), who found from a review of wildfire case studies an average crown fire rate of spread of about 1.5 miles/hour or 115 chains/hour (39 m/min or 2.3 km/hr) (figure 5).

Crowning wildfires have been known to make sustained runs of 18.5 to 40 miles (30 to 65 km) over flat and rolling to gently undulating ground during a single burning period and over multiple days. For example, the Lesser Slave Fire in central Alberta advanced 40 miles (64 km) through a variety of boreal forest fuel types in a period of 10 hours on May 23, 1968 (Kiil and Grigel 1969), resulting in an average rate of spread of 320 chains/hour (107 m/min). Peak spread rates in crowning wildfires associated with short bursts of fire activity have been reported to reach 695 chains/hour (235 m/min) (Keeves and Douglas 1983).

In some conifer forest fuel types exhibiting discontinuous or very low quantities of surface fuels, surface fire spread is nearly nonexistent even under moderately strong winds. However, once a certain wind speed threshold is reached with respect to given level

of fuel dryness, a dramatic change to crown fire spread can suddenly occur (Bruner and Klebenow 1979, Hough 1973).

Slope steepness dramatically increases the uphill rate of spread and intensity of wildland fires by exposing the fuel ahead of the advancing flame front to additional convective and radiant heat. As slope steepness increases, the flames tend to lean more and more toward the slope surface, gradually becoming attached, the result being a sheet of flame moving roughly parallel to the slope. Fires advancing upslope are thus capable of making exceedingly fast runs compared to those on level topography. A crown fire burning on to a 35-percent slope can be expected to spread about 2.5 times as fast as one on level terrain for the same fuel and weather conditions (figure 6).

The overall advance of crown fires in mountainous terrain tends to be well below what would be expected on flat ground, even under extreme

fire weather conditions. This is most likely due to major topographical barriers to fire spread, differences in fuel moisture according to slope aspect, and the degree of terrain exposure to the prevailing winds, which limits the full effectiveness of wind speed on fire spread (Chandler and others 1963, Schroeder and Buck 1970). When wind and topography become favorably aligned, exceedingly rapid fire growth can be expected for brief periods over short distances.

It is worth highlighting the fact that crown fire runs in mountainous terrain are not strictly limited to upslope situations. Cases of crown fires burning downslope or cross-slope under the influence of strong winds have occurred (Goens and Andrews 1998).

Caution in the Use of Fire Behavior Models To Judge Fuel Treatment Effectiveness

Cruz and Alexander (2014) explored the relative variation in predicted

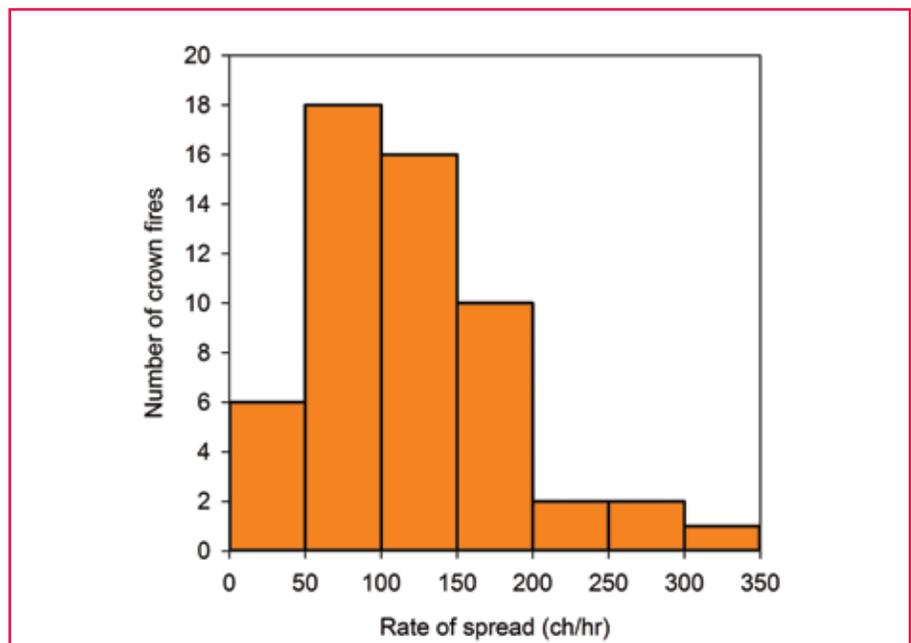


Figure 5.—The distribution of active crown fire rates of spread based on observations of 57 Canadian and American wildfires compiled by Alexander and Cruz (2006).

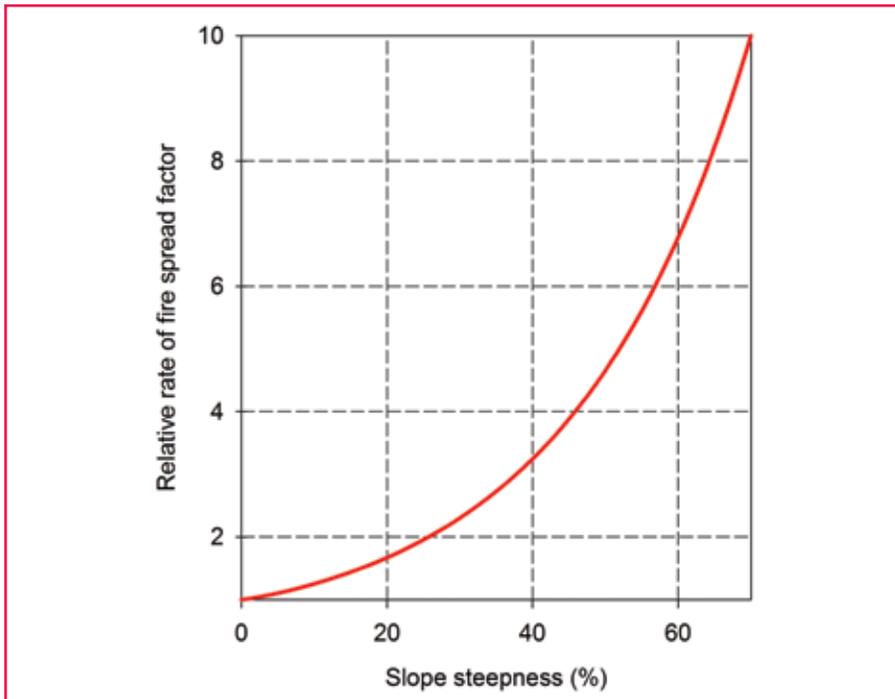


Figure 6.—The effect of slope steepness on the uphill rate of spread of free-burning wildland fires in the absence of wind according to Van Wagner (1977b).

fireline intensity and the wind speed thresholds for the onset of crowning and active crown fire spread in a lodgepole pine stand subjected to a commercial thinning operation. Seven distinct environmental scenarios, each with different assumptions regarding the estimation of fine dead fuel moisture contents and fire behavior models used, were examined. The results from the seven scenarios varied widely, sometimes exhibiting contradictory trends. This case study emphasized the care that must be taken in selecting realistic environmental inputs and what fire behavior characteristics are chosen for analysis.

Major Assumptions Associated With Van Wagner’s (1977a) Models of Crown Fire Initiation and Propagation

- The conifer forest stand possesses a minimum canopy-bulk density that will allow flames to

propagate vertically through the canopy-fuel layer.

- Bridge or ladder fuels such as bark flakes on tree boles, tree lichens, shrubs and understory trees, dead bole branches, and suspended needles exist in sufficient quantity to intensify the surface fire and extend the flame height.
- The empirical constants incorporated in the models based on experimental fires carried out in a red pine plantation fuel complex and the attendant burning conditions are appropriate to other conifer forest stand types and situations.
- The function for foliar moisture content is based on the theoretical premise that all of the moisture in the fuel is driven off before ignition can occur.

The Myth of the Conditional Crown Fire

Scott and Reinhardt (2001) claimed that the possibility exists for a stand to support an active crown

fire that would otherwise not initiate a crown fire. They referred to this situation as a “conditional surface fire.” Later on, Scott (2006) termed this a “conditional crown fire.” To our knowledge, no empirical proof has been produced to date to substantiate the possible existence of such a situation, at least as a steady-state phenomenon. The concept assumes constant wind speed, failing to recognize the transient nature of fire propagation with bursts of high rates of spread occurring during gusts in the wind followed by periods of lower spread rates and intensity during lulls.

Empirical- and Physics-Based Models To Predict the Onset of Crowning in Conifer Forests

Probability of Crown Fire Initiation

Cruz and others (2003) modeled the initiation of crown fires in conifer stands using logistic regression analysis by considering as independent variables a basic physical descriptor of the fuel complex structure and selected components of the Canadian Forest Fire Weather Index (FWI) system. The study was based on a fire behavior research database consisting of experimental surface and crown fires ($n = 63$) covering a relatively wide range of burning conditions and fuel type characteristics.

Four models were built with decreasing input needs. Significant predictors of crown fire initiation were canopy-base height, 33-foot (10 m) open wind speed, and four components of the FWI (that is, fine fuel moisture code, drought code, initial spread index, and buildup index). The models predicted correctly the type of fire (surface

or crown) between 66 and 90 percent of the time.

The results of a limited evaluation involving two independent experimental fire data sets for distinctly different fuel complexes were encouraging. The logistic models built may have applicability in fire management decision-support systems, allowing for the estimation of the probability of crown fire initiation at small and large spatial scales from commonly available fire environment and fire danger rating information. The relationships presented are considered valid for free-burning fires on level terrain in coniferous forests that have reached a pseudosteady state and are not deemed applicable to dead conifer forests (that is, insect-killed stands).

Probability of Crown Fire Occurrence

Cruz and others (2004) developed a model to predict the probability of crown fire occurrence based on three fire environment variables (open wind speed, fuel strata gap, and fine dead fuel moisture) and one fire behavior descriptor (an estimate of surface fuel consumption). They developed the model on the basis of experimental surface and crown fires ($n = 71$) covering a wide spectrum of fire environments and fire behavior characteristics and encompassing fuel complexes with diverse structures. Interestingly, foliar moisture content was not found to be significantly related to the likelihood of crown fire activity.

The model output is the likelihood or probability of a crown fire occurring. This output allows a user to interpret the results differently from the dichotomous answer offered by deterministic models

(that is, crowning or no crowning). Based on the user experience with the model output in a particular fuel type, key threshold values for the onset of crowning can be locally determined for particular conifer forest types.

Evaluation of the model yielded encouraging results concerning its validity. An interesting advantage of this model over other approaches for determining the initiation of crown fires is its simplicity. The output (that is, the onset of crowning) is directly related to the main controlling environmental variables, thereby limiting error propagation. In some modeling systems (for example, BehavePlus), a number of intermediate computations—such as rate of fire spread and flame front residence time—must first be made before fireline intensity can be calculated. The resultant value is then used to predict flame length, as well as the onset of crowning or lethal crown scorch height. In the process of determining these primary outputs, compounding errors can arise from the choice of fuel model and fuel availability for flaming combustion, resulting in large overall errors (Cruz and others 2004, Cruz and Alexander 2010).

The Crown Fuel Ignition Model

Cruz and others (2006a) developed a semi-physical model to predict the ignition of conifer forest crown fuels above a surface fire based on heat transfer theory. The Crown Fuel Ignition Model (CFIM) integrates (1) the characteristics of the energy source as defined by surface fire flame front properties, (2) buoyant plume dynamics, (3) heat sink as described by the crown fuel particle characteristics, and (4) energy transfer (gain and losses) to the crown fuels. The final model output is the temperature of the crown

fuel particles, which upon reaching ignition temperature are assumed to ignite. CFIM predicts the ignition of crown fuels but does not determine the onset of crown fire spread *per se*. The coupling of the CFIM with models determining the rate of propagation of crown fires allows for the prediction of the potential for sustained crowning. CFIM has been incorporated into a fire behavior prediction system for exotic pine plantations in Australia (Cruz and others 2008).

Model evaluation (Cruz and others 2006b) indicated that the primary factors influencing crown fuel ignition are those determining the depth of the surface fire burning zone (that is, fuel available for flaming combustion), wind speed, moisture content of surface fuels, and the vertical distance between the ground/surface fuel strata and the lower boundary of the crown fuel layer. Intrinsic crown fuel properties, such as foliar moisture content and leaf size, were found to have a minor influence on the process of crown fuel ignition. Comparison of model predictions against data collected in high-intensity experimental fires and predictions from other models gave encouraging results relative to the validity of the model system.

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Torching Does Not Constitute a Form of Crowning

The concept of passive crowning implies an element of forward movement or propagation of the flame front. The incidental ignition of an isolated tree or clump of trees, with the flames spreading vertically from the ground surface through the crown(s) without any form of forward spread following, does not constitute passive crowning. Flame defoliation of conifer trees by what amounts to stationary torching or “crowning out,” especially common during the postfrontal combustion stage following passage of the surface fire, generally does not generate any kind of horizontal spread.



Torching lodgepole pine tree during an experimental fire undertaken near Prince George, BC (from Lawson 1972).

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ENERGY RELEASE RATES, FLAME DIMENSIONS, AND SPOTTING CHARACTERISTICS OF CROWN FIRES



Martin E. Alexander and Miguel G. Cruz

When a fire in a conifer forest stand crowns, additional fuel is consumed primarily in the form of needle foliage but also in mosses and lichens, bark flakes, and small woody twigs. The additional canopy fuel consumed by a crown fire combined with the increase in rate of fire spread after crowning can easily lead to the quadrupling of fireline intensity and, in turn, a dramatic increase in flame size within a few seconds (for example: from 800 to 3,200 British thermal units/second-foot [Btu/sec-ft]). Spotting activity can also very quickly increase in both density and distance. In such cases, there is little wonder why crown fires just seem to literally “blow up” (Byram 1959).

As the fireline intensity or rate of energy released per unit area of the flame front increases (figure 1A); flame size or volume increases due to a faster rate of spread and a larger quantity of fuel being volatilized in the flaming front. The relative increase in fireline intensity from a surface fire to full-fledged crowning in a conifer forest stand, as shown in figure 1A, will depend on the surface fuelbed characteristics and the canopy base height. Fireline

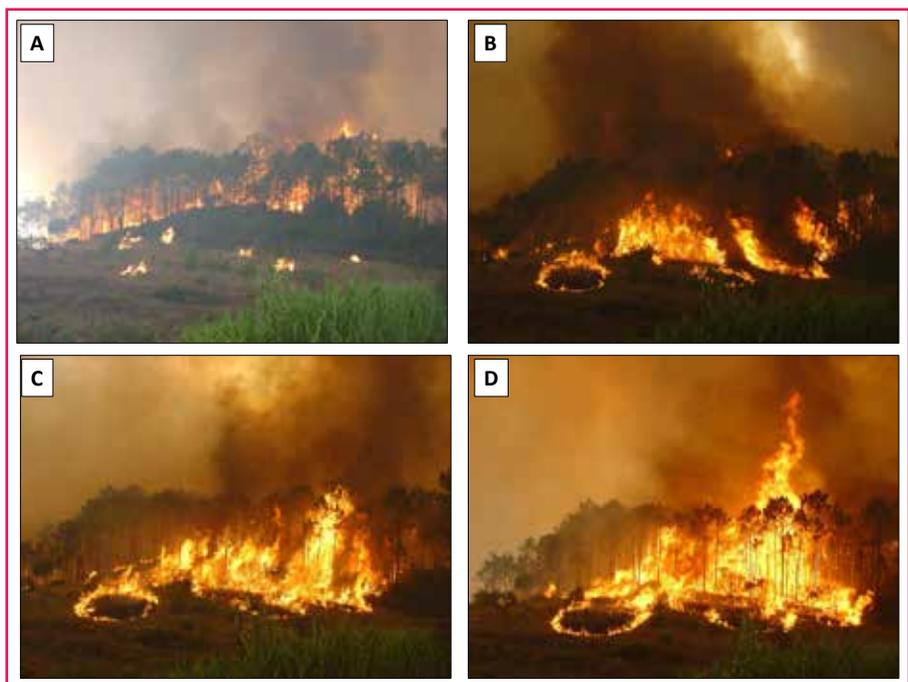
intensities of wind-driven crown fires can easily reach 9,000 Btu/sec-ft and occasionally exceed 25,000 Btu/sec-ft (Anderson 1968).

Flame Front Dimensions

A fire’s flame zone characteristics (depth, angle, height, and length) are a reflection of its heat or energy release rate. The flame depth of a spreading wildland fire is a product of its spread rate multiplied by the flame front residence time. The latter quantity represents the duration that a moving band or zone of continuous flaming combustion persists at or resides over a given

location. Flame front residence times are dictated largely by the particle size(s) distribution, load, and compactness of the fuelbed (Nelson 2003).

Flame front residence times for conifer forest fuel types at the ground surface have been found to vary from 30 seconds to a minute (Taylor and others 2004), compared to 5 to 10 seconds in fully cured grass fuels (Cheney and Sullivan 2008). Crown fires are capable of producing very deep flame fronts (see figure 1B). The depth of the burning zone in the surface fuels of



Sequence of photos taken during the afternoon of August 22, 2005, near Coimbra, Portugal, showing some of the complexities involved in free-burning wildland fire behavior. An advancing wildfire in a maritime pine forest spotted into an opening (A), followed by (B and C) spot fires coalescing, and (D) merging with the main flame front, resulting in a greatly increased flame height. The elapsed time between photos (A) and (D) was approximately 105 seconds. Photos by M.G. Cruz.

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a crown fire spreading at 66 yards/minute (60 m/min) would, for example, be around 49 yards/minute (45 m: $60 \times 0.75 = 45$). Residence times within the canopy fuel layer of a crown fire are approximately one-half to one-third those experienced at ground level (Despain and others 1996). This is reflected in the gradual convergence of the flaming zone depth with height, ending in the flame tip above the tree crowns.

The flame front of a crown fire on level ground appears to be vertical or nearly so (Stocks 1987). This appearance has led to the popular phrase “wall of flame” when it comes to describing crown fire behavior. The fact that the flames of a crown fire stand so erect is a direct result of the powerful buoyancy associated with the large amount of energy released in the flame front.

Radiation from the crown fire flame front can produce painful burns on exposed skin at more than 109 yards (100 m) from the fire edge. Such would have been the case during the major run of the 1985 Butte Fire on the Salmon National Forest in central Idaho had firefighters not had protective fire shelters to avert thermal injuries (Mutch and Rothermel 1986).

Given the difficulty of gauging the horizontal depth of the burning zone in a crown fire, flame height constitutes a more easily visualized dimension than flame length. However, efforts to objectively estimate flame heights of crown fires are complicated by the fact that sudden ignition of unburned gases in the convection column can result in flame flashes that momentarily extend some 300 feet (90 m) or more into the convection column aloft. Such flashes can easily result in overestimates of average

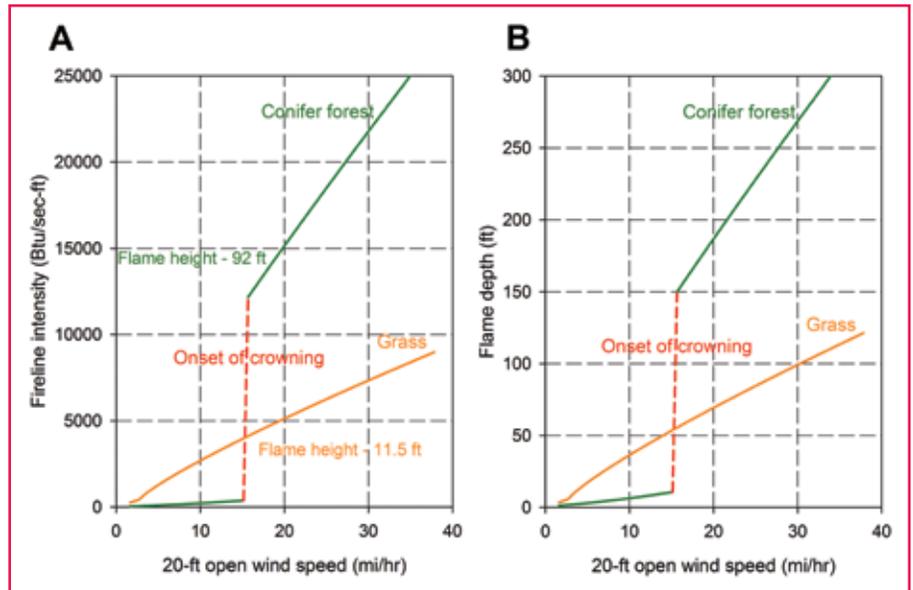


Figure 1.—The variation in (A) fireline intensity and (B) flame depth in relation to wind speed for a conifer forest stand compared to a grassland fuel complex (after Alexander and Cruz 2011). The “kink” in the curves associated with the conifer forest represents the point of surface-to-crown fire transition.

flame heights, which usually range from about 50 to 150 feet (15 to 45 m) on high-intensity crown fires (Byram 1959).

The average flame heights of active crown fires are generally regarded as being about two to possibly three times the stand height (Stocks 1987, Stocks and others 2004). This simple rule of thumb is not applicable to tall—say, 80 feet (25 m)—conifer forest stands with moderately high canopy base heights (that is: greater than 40 feet/12 m) unless a dense understory tree component exists (Burrows and others 1989).

Spotting Activity

The general effect of spotting on crown fire rate of spread is determined by the density of ignitions and distances of these ignitions ahead of the main fire. These two characteristics are intimately linked, as density typically decreases with increased distance from the main advancing flame front.

Spotting from crown fires is also effective in breaching major barriers

to fire spread, including large water bodies and other nonfuel areas (for example, rock slides or barren ground). Thus, constructing fuelbreaks comprised of vegetation of low flammability can, depending on their width, be an effective buffer against crown fires—but only to a point.

When fire environment conditions are uniform and winds aloft are favorable, spotting can contribute to the overall spread and growth of crown fires provided that the spot fires are able to burn independently of the main advancing fire front. In most high-intensity wildfires that involve crowning, spot fires originating ahead of the advancing flame front are typically overrun and thus incorporated into the larger fire perimeter before they are able to develop and spread independently or otherwise be influenced by the main fire (for example: by in-draft winds).

For a crown fire spreading at a rate of 150 chains/hour (50 m/min) or 1.9 miles/hour (3.0 km/hr) and burning under homogeneous fuel,

weather, and topographic conditions, spotting distances would have to exceed approximately 1,650 to 2,300 feet (500 to 700 m)—depending on the ignition delay which can be as much as 5.0 to 10 minutes—to have the potential to increase a fire’s overall rate of spread through a “leap frog” effect (figure 2). If there are sufficient spot fires at or just beyond this distance and they can rapidly coalesce, this “mass ignition” effect will temporarily lead to the formation of pseudoflame fronts (Wade and Ward 1973) with greatly increased flame heights.

Spotting distances of up to about 1.2 miles (2 km) are commonly observed on wind-driven crown fires in conifer forests, but spotting distances close to 3.1 miles (5 km) have been documented (Haines and Smith 1987). Spot fire distances of 3.7 to 6.2 miles (6 to 10 km) were reported to have occurred in the Northern Rocky Mountains during the 1910 and 1934 fire seasons (Gisborne 1935).

Under exceptional circumstances, spotting distances greater than 6.2 miles (10 km) have been described. Especially noteworthy are the 10- to 12-mile (16 to 19 km) spot fire distances associated with the 1967 Sundance Fire in northern Idaho (Anderson 1968). Similar distances are reported to have occurred in radiata pine plantations during the major run of the 1983 Mount Muirhead Fire in South Australia (Keeves and Douglas 1983), although the responsible embers may have arisen from native eucalypt trees within the plantation.

Estimating Maximum Spot Fire Distances

Albini (1979) developed a physical-based model for predicting the

maximum spotting distance from single or group tree torching that covers the case of intermediate-range spotting of perhaps 1 to 2 miles (1.5 to 3.0 km); he also devel-

oped similar models for burning piles of slash or “jackpots” of heavy fuels and wind-aided surface fires in non-tree canopied fuel complexes such as grass, shrubs, and logging

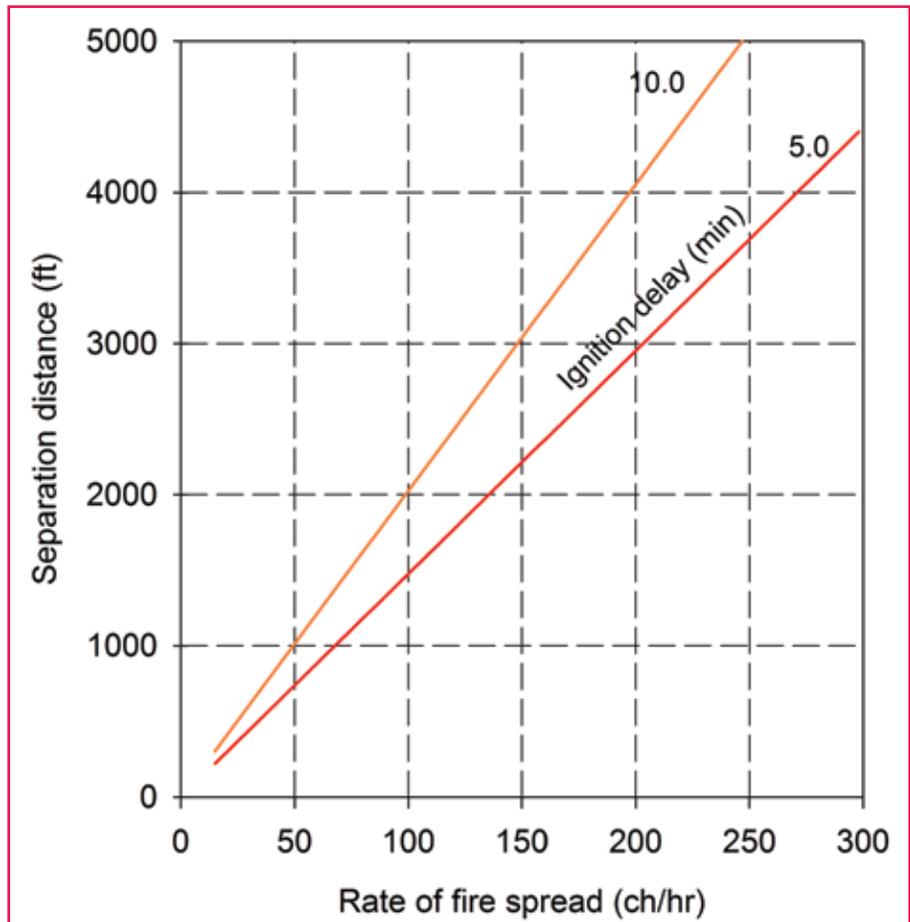


Figure 2.—Minimum separation distance required for a newly ignited spot fire to avoid being overrun by the main flame front of an advancing crown as a function of rate of spread and ignition delay (after Alexander and Cruz 2006). Ignition delay represents the elapsed time between a firebrand alighting, subsequent ignition, and the onset of fire spread.

Wildfire Observations of Spotting Distances†

Behavior records including rate of spread were made during 33 days of observation on 10 large fires in Oregon and Washington. With one possible exception, most of the spread resulted from wind-carried embers that started spot fires ahead of the main fire. As

†Adapted from U.S. Department of Agriculture (1952)

fuels became drier, volume of fuel greater, or wind stronger, the rate of spread by spotting increased. Spot fires ¼-mile (0.4 km) ahead of the main fire were common and, in a few cases, spot fires suddenly appeared as far as 2 miles (3.2 km) ahead of any other visible fire.

slash. As with any of Albini's maximum spot fire distance models, determining whether a given ember or firebrand will actually cause a spot fire must still be assessed based on its ignition probability.

A predictive system was recently developed for estimating the maximum spotting distance from active crown fires as a function of the firebrand particle diameter upon alighting on the surface fuelbed based on three inputs: canopy top height, free flame height (that is: flame distance above the canopy top height), and the wind speed at the height of the canopy (Albini and others 2012). Although the system has not been specifically validated, the estimates produced by the system (figure 3) appear realistic in light of existing documented observations.

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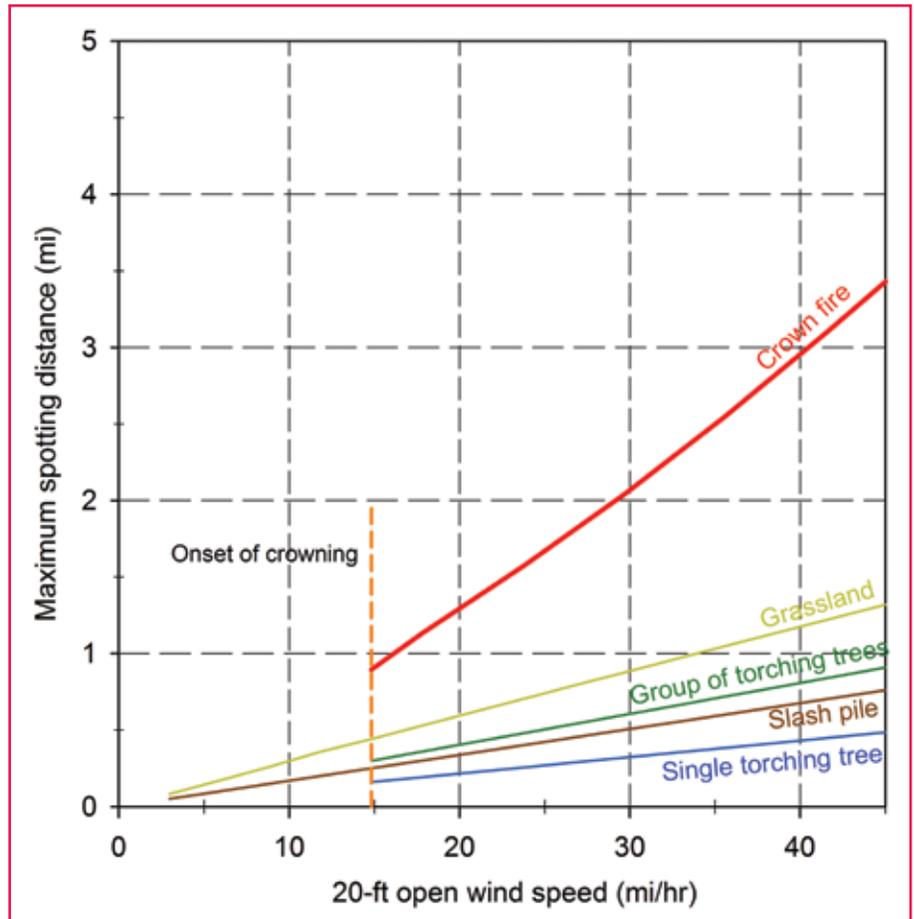


Figure 3.—Comparison of predictions for maximum potential spotting distance over level terrain as a function of wind speed, based on models developed by Frank A. Albini (after Albini and others 2012).

THE ELLIPTICAL SHAPE AND SIZE OF WIND-DRIVEN CROWN FIRES



Martin E. Alexander and Miguel G. Cruz

Typically, for wildfires in conifer forests to become large, some degree of crowning must occur. A common axiom in wildland fire management is that approximately 95 percent of area burned is generally caused by less than about 5 percent of the fires.

A forest fire at the very minimum doubles its spread rate after the onset of crowning, and the area burned for a given period will be at least four times what would have been covered by a surface fire. In other words: the area burned is proportional to the rate of spread increase (following the transition to crowning) to the power of 2. Thus, if a fire triples its rate of advance after crowning, the area burned will be nine times greater than had it remained as a surface fire ($3.0^2 = 9$).

Maximum Fire Growth Potential of Crown Fires

Other than dry and plentiful fuels, the principal ingredients for major crown fire runs are strong, sustained winds coupled with extended horizontal fuel continuity. For example, more than 80 percent of the final area burned of 110,000

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Wind-driven surface and crown fires in conifer forests typically adopt a roughly elliptical shape.

acres (44,520 ha) during the major run of the Buckhead Fire in north Florida occurred during a 10- to 12-hour period on March 24–25, 1956.

Under favorable conditions, crown fires, such as the Lesser Slave Lake Fire in central Alberta, covered an area in excess of 173,000 acres (70,000 ha) in a single, 10-hour burning period on May 23, 1968 (Kiil and Grigel 1969). Similarly,

the Canyon Creek in western Montana burned over an area of some 180,000 acres (72, 850 ha), principally after crowning, during a 16-hour run in mountainous topography on September 6–7, 1988 (Goens 1990).

The Length-to-Breadth Ratio of Elliptical-Shaped Fires

Provided the wind direction remains relatively constant and the fire environment is otherwise uniform, wind-driven surface and crown fires in conifer forests typically adopt a roughly elliptical shape (Anderson 1983, Van Wagner 1969) defined by its length-to-breadth ratio (L:B) (figure 1A), which in turn is a function of wind

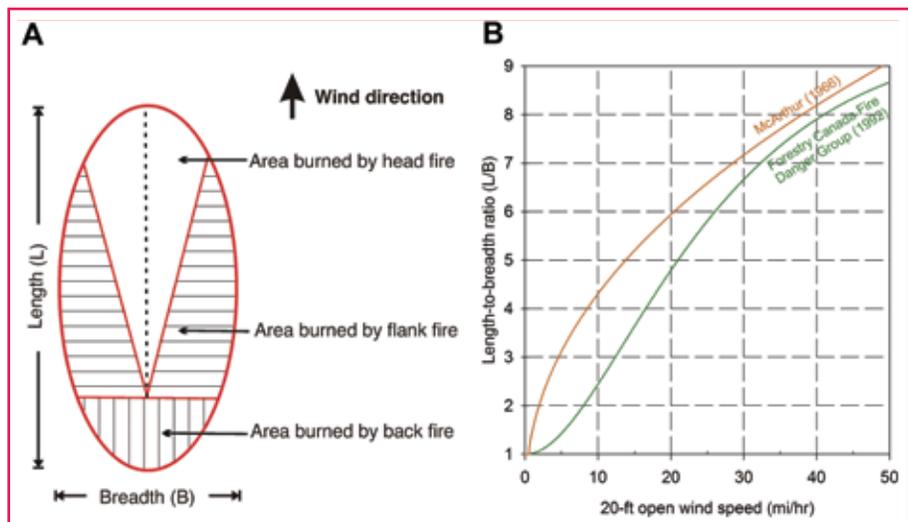


Figure 1. —(A) Schematic diagram of a simple elliptical fire growth model (after Van Wagner 1969) with the point of ignition represented by the junction of the four area growth zones and (B) the length-to-breadth ratio of elliptical shaped surface and crown fires in conifer forests on level to gently undulating terrain as a function of wind speed for conifer forests (Forestry Canada Fire Danger Group 1992) and grasslands (McArthur 1966).

speed (figure 1B). The L:B associated with crown fires generally ranges from a little less than 2.0 to about 6.0—with a maximum of approximately 8.0 to 9.0 in exceptional cases—whereas heading surface fires in conifer forests commonly have an L:B less than 2.0 (Alexander 1985).

Rothermel (1991) developed a model for predicting the L:B of crown fires as a function of wind speed based on the previous work of Anderson (1983) and Andrews (1986) involving laboratory-scale test fires. Empirical observations garnered from wildfires suggests that his model underpredicts L:B for wind-driven crown fires (Alexander and Cruz 2011).

Estimating Area Burned and Perimeter Length of Elliptical-Shaped Crown Fires

Assuming the presence of continuous fuels, no major barriers to fire spread, and no major change in wind and fuel moisture conditions, the forward spread distance of a crown fire can be determined by multiplying its predicted rate of spread by a projected elapsed time. Crown fire rates of spread can be obtained from a model like that of Cruz and others (2005). Estimates of potential crown fire size in

A Description of the 1956 Buckhead Fire[†]

The Buckhead Fire, one of the four largest in the Southeast, burned nearly 110,000 acres (44,520 ha) in north Florida during the last week in March 1956. Approximately one-third of this acreage was on the Osceola National Forest. Probably as much as 90,000 acres (36,425 ha) of the final area was burned in a 10- to 12-hour period, starting shortly after 9:00 p.m. on the night of March 24. At the peak of its intensity, the rate of energy output of this fire was comparable to that of a summer thunderstorm.

Like the other three fires, as well as a Maine conflagration in 1947, the Buckhead was a cold-front fire. Although these fires made their major runs during

[†]Adapted from U.S. Department of Agriculture (1957)

the passage of a dry cold front, their large size was due in part to severe burning conditions prior to the arrival of the front. During this earlier period, the winds were usually in the quadrant between south and west, and the direction of spread was most likely to be in the quadrant between east and north. With the arrival of the cold front, the wind shifted rapidly to the northwest or north, thus causing the right flank of the original fire to form a number of high-intensity heads, which travelled toward the south or southeast. In the case of the Buckhead Fire, right flank became the head. The only exception to the typical pattern was that the frontal system was oriented such that the prefrontal winds were in a west or slightly north of west direction and the wind eventually shifted to an east of north direction.

terms of area burned and perimeter length can then be made based on the wind speed used in the prediction. Tabulations similar to those of Rothermel (1991) are presented in tables 1 and 2.

The simplistic picture of fire growth described here is applicable

to cases involving a point source ignition, such as an escaped campfire or prescribed fire hold-over, lightning fire start, or a breach in an established control line, over approximately 1 to 8 hours. The approach is not as applicable in estimating the growth of a crown fire when the perimeter becomes highly irregular in shape with the passage of time as a result of changes in wind direction, fuel types, and terrain characteristics.

Area burned is proportional to the rate of spread increase (following the transition to crowning) to the power of 2.

Table 1.—Elliptical fire area in acres for a wind-driven crown fire on level terrain to gently undulating terrain as a function of its forward spread distance and the prevailing wind speed based on the Canadian Forest Fire Behavior Prediction System (Forestry Canada Fire Danger Group 1992). This tabulation also includes the elliptical-shaped fire’s length-to-breadth ratio (L:B) as a function of wind speed.

| Forward spread distance (miles) | 20-foot open wind speed (miles per hour) | | | | | | | | |
|---------------------------------|--|---------|---------|---------|---------|---------|---------|---------|---------|
| | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| | Elliptical fire area (acres) | | | | | | | | |
| 0.25 | 17 | 12 | 9 | 7 | 6 | 5 | 5 | 4 | 4 |
| 0.5 | 67 | 47 | 35 | 28 | 24 | 21 | 19 | 18 | 17 |
| 1 | 269 | 187 | 140 | 113 | 96 | 84 | 76 | 70 | 66 |
| 1.5 | 605 | 420 | 316 | 254 | 215 | 189 | 171 | 159 | 149 |
| 2 | 1,075 | 746 | 561 | 452 | 383 | 337 | 305 | 282 | 265 |
| | | | | | | | | | |
| 4 | 4,301 | 2,984 | 2,245 | 1,807 | 1,531 | 1,347 | 1,219 | 1,127 | 1,060 |
| 6 | 9,677 | 6,715 | 5,051 | 4,066 | 3,444 | 3,030 | 2,743 | 2,536 | 2,384 |
| 8 | 17,204 | 11,937 | 8,979 | 7,228 | 6,123 | 5,387 | 4,876 | 4,509 | 4,239 |
| 10 | 26,881 | 18,652 | 14,030 | 11,294 | 9,567 | 8,418 | 7,619 | 7,046 | 6,624 |
| 12 | 38,709 | 26,858 | 20,204 | 16,264 | 13,777 | 12,121 | 10,971 | 10,146 | 9,538 |
| | | | | | | | | | |
| 14 | 52,687 | 36,557 | 27,499 | 22,136 | 18,752 | 16,498 | 14,933 | 13,809 | 12,982 |
| 16 | 68,816 | 47,748 | 35,918 | 28,913 | 24,492 | 21,549 | 19,504 | 18,037 | 16,956 |
| 18 | 87,095 | 60,431 | 45,458 | 36,593 | 30,998 | 27,273 | 24,685 | 22,828 | 21,460 |
| 20 | 107,525 | 74,606 | 56,121 | 45,176 | 38,269 | 33,670 | 30,475 | 28,182 | 26,494 |
| 22 | 130,105 | 90,273 | 67,907 | 54,663 | 46,306 | 40,741 | 36,875 | 34,101 | 32,058 |
| | | | | | | | | | |
| 24 | 154,836 | 107,433 | 80,815 | 65,054 | 55,108 | 48,485 | 43,884 | 40,583 | 38,152 |
| 26 | 181,717 | 126,084 | 94,845 | 76,348 | 64,675 | 56,902 | 51,503 | 47,628 | 44,776 |
| 28 | 210,749 | 146,228 | 109,998 | 88,546 | 75,008 | 65,993 | 59,732 | 55,238 | 51,929 |
| 30 | 241,931 | 167,864 | 126,273 | 101,647 | 86,106 | 75,758 | 68,569 | 63,410 | 59,612 |
| 32 | 275,264 | 190,991 | 143,671 | 115,652 | 97,970 | 86,195 | 78,017 | 72,147 | 67,826 |
| | | | | | | | | | |
| 34 | 310,747 | 215,611 | 162,191 | 130,560 | 110,598 | 97,306 | 88,074 | 81,447 | 76,569 |
| 36 | 348,381 | 241,723 | 181,833 | 146,372 | 123,993 | 109,091 | 98,740 | 91,311 | 85,842 |
| 38 | 388,165 | 269,328 | 202,598 | 163,087 | 138,152 | 121,549 | 110,016 | 101,738 | 95,645 |
| 40 | 430,100 | 298,424 | 224,485 | 180,706 | 153,077 | 134,680 | 121,901 | 112,730 | 105,978 |
| | | | | | | | | | |
| L:B | 1.9 | 2.7 | 3.6 | 4.4 | 5.3 | 6.0 | 6.6 | 7.1 | 7.6 |

Table 2.—Elliptical fire perimeter in miles for a wind-driven crown fire on level to gently undulating terrain as a function of its forward spread distance and the prevailing wind speed, based on the Canadian Forest Fire Behavior Prediction System (Forestry Canada Fire Danger Group 1992). This tabulation also includes the elliptical-shaped fire's length-to-breadth ratio (L:B) as a function of wind speed.

| Forward spread distance (miles) | 20-foot open wind speed (miles per hour) | | | | | | | | |
|---------------------------------|--|------|------|------|------|------|------|------|------|
| | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| | Elliptical fire perimeter (miles) | | | | | | | | |
| 0.25 | 0.6 | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 0.5 | 1.2 | 1.1 | 1.1 | 1.1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 1 | 2.5 | 2.3 | 2.2 | 2.1 | 2.1 | 2.1 | 2.1 | 2.0 | 2.0 |
| 1.5 | 3.7 | 3.4 | 3.3 | 3.2 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 |
| 2 | 4.9 | 4.5 | 4.3 | 4.2 | 4.2 | 4.1 | 4.1 | 4.1 | 4.1 |
| | | | | | | | | | |
| 4 | 9.9 | 9.1 | 8.7 | 8.5 | 8.3 | 8.3 | 8.2 | 8.2 | 8.2 |
| 6 | 14.8 | 13.6 | 13.0 | 12.7 | 12.5 | 12.4 | 12.3 | 12.3 | 12.2 |
| 8 | 19.7 | 18.1 | 17.4 | 16.9 | 16.7 | 16.5 | 16.4 | 16.4 | 16.3 |
| 10 | 24.7 | 22.7 | 21.7 | 21.2 | 20.9 | 20.7 | 20.5 | 20.5 | 20.4 |
| 12 | 29.6 | 27.2 | 26.0 | 25.4 | 25.0 | 24.8 | 24.7 | 24.5 | 24.5 |
| | | | | | | | | | |
| 14 | 34.5 | 31.7 | 30.4 | 29.6 | 29.2 | 28.9 | 28.8 | 28.6 | 28.6 |
| 16 | 39.5 | 36.3 | 34.7 | 33.9 | 33.4 | 33.1 | 32.9 | 32.7 | 32.6 |
| 18 | 44.4 | 40.8 | 39.0 | 38.1 | 37.6 | 37.2 | 37.0 | 36.8 | 36.7 |
| 20 | 49.3 | 45.3 | 43.4 | 42.3 | 41.7 | 41.3 | 41.1 | 40.9 | 40.8 |
| 22 | 54.3 | 49.9 | 47.7 | 46.6 | 45.9 | 45.5 | 45.2 | 45.0 | 44.9 |
| | | | | | | | | | |
| 24 | 59.2 | 54.4 | 52.1 | 50.8 | 50.1 | 49.6 | 49.3 | 49.1 | 48.9 |
| 26 | 64.1 | 58.9 | 56.4 | 55.0 | 54.2 | 53.7 | 53.4 | 53.2 | 53.0 |
| 28 | 69.1 | 63.5 | 60.7 | 59.3 | 58.4 | 57.9 | 57.5 | 57.3 | 57.1 |
| 30 | 74.0 | 68.0 | 65.1 | 63.5 | 62.6 | 62.0 | 61.6 | 61.4 | 61.2 |
| 32 | 78.9 | 72.5 | 69.4 | 67.7 | 66.8 | 66.1 | 65.7 | 65.5 | 65.3 |
| | | | | | | | | | |
| 34 | 83.9 | 77.1 | 73.7 | 72.0 | 70.9 | 70.3 | 69.8 | 69.6 | 69.3 |
| 36 | 88.8 | 81.6 | 78.1 | 76.2 | 75.1 | 74.4 | 74.0 | 73.6 | 73.4 |
| 38 | 93.7 | 86.2 | 82.4 | 80.4 | 79.3 | 78.5 | 78.1 | 77.7 | 77.5 |
| 40 | 98.7 | 90.7 | 86.8 | 84.7 | 83.4 | 82.7 | 82.2 | 81.8 | 81.6 |
| | | | | | | | | | |
| L:B | 1.9 | 2.7 | 3.6 | 4.4 | 5.3 | 6.0 | 6.6 | 7.1 | 7.6 |

Measures of the Rate of Crown Fire Growth

The rate of area growth is the speed at which a fire increases its size, expressed in terms of area per unit of time (for example: in acres per hour) applied to current moment only. The rate of fire area growth does not remain constant with time but rather increases in direct proportion to time. Assuming a steady-state rate of fire spread, the total area burned increases as the square of time since ignition (Van Wagner 1969).

The rate of perimeter growth is the speed at which a fire increases its perimeter, expressed in terms of distance per unit of time (for example: in miles per hour). In contrast to the rate of area growth, the rate of perimeter growth remains constant with time provided the head fire rate of spread remains unchanged (Van Wagner 1965). The rate of perimeter growth can be quickly estimated by multiplying the predicted head fire rate of spread by a factor of 2.5. This rate is based on winds of about 15 miles/hour (25 km/h).

Probably the worst behavior characteristic of cold-front fires is long-distance spotting. In the Buckhead Fire, embers were carried as much as 3 miles (4.8 km) ahead of the main fire, though most of the spotting was ~1 mile (1.6 km) or less. At times, ember showers within this distance produced firestorm effects by simultaneous ignition over extensive areas.

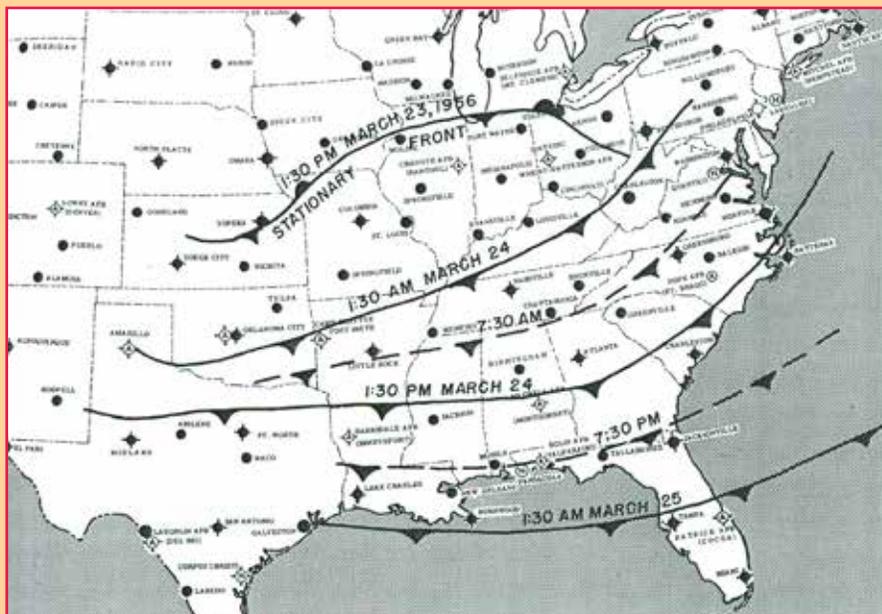
A conflagration potential had been established by drought conditions that had persisted for

more than a year. A low water table in the swamps had made available large volumes of fuel that, in normal conditions, would not burn.

Considering the drought, turbulence, and low-level jet winds, the behavior of the Buckhead Fire was not a mystery. The behavior characteristics of this fire had shown up on previous large fires with similar conditions. For a period of 10 hours preceding the arrival of the cold front in north Florida, the low-level jet winds associated with the front were making their appearance in an area extending from northern Alabama to the upper Piedmont of South Carolina. The cold front was moving at a speed of about 25 miles/hour (40 km/h). The accompanying map shows the position of the front at 6-hour intervals from 1:30 a.m., March 24, to 1:30 a.m., March 25. Broken lines represent the estimated position of the front at 7:30 a.m. and 7:30 p.m. on March 24. This rapidly moving cold

front started as a stationary front, the position of which is shown at 1:30 p.m. on March 23, when it extended across the northern part of the Central States.

The progressive southward movement of the dry cold front and corresponding southward movement of severe atmospheric conditions associated with it illustrate what precision forecasts could contribute to fire control operations on a cold-front fire. There were two periods in the course of this fire prior to the major blowup when knowledge of approaching turbulence and low-level jet winds would have brought into operation control measures that otherwise might not have been justified. Whether or not such measures would have stopped the fire's major run remains unknown, but the question itself points out the key role that precision forecasts could play when a conflagration potential exists.



The progressive southward movement of the cold front associated with the major run of the 1956 Buckhead Fire in north Florida.

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OPERATIONAL PREDICTION OF CROWN FIRE BEHAVIOR



Miguel G. Cruz and Martin E. Alexander

Operational guides for predicting various aspects of wildland fire behavior, including crowning, are generally dependent on mathematical models that can take a variety of forms. The degree of accuracy in predictions of crown

fire behavior is dependent on the model's applicability to a given situation, the validity of the model variables' relationships, and the reliability of the model input data (Alexander and Cruz 2013).

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Rothermel's Surface and Crown Fire Rate-of-Spread Models

Rothermel (1972) developed a model for predicting a surface fire's rate of spread and intensity that forms the basis for most of the decision aids used in predicting fire

An Observation Regarding Surface Versus Crown Fires

"The prediction of surface fire behavior is, in fact, probably more difficult than the prediction of crowning potential because of the multiplicity of possible forest floor and understory fuel complexes."—
Van Wagner (1979)



Flame front associated with experimental crown fire in a jack pine (*Pinus banksiana*)–black spruce (*Picea mariana*) forest, Plot S1, International Crown Fire Modelling Experiment, Northwest Territories Canada. Photo by M.G. Cruz.

behavior today in the United States (Andrews 2013). Field application is dependent on either a stylized or custom-built fuel model, that is a simulated surface fuel complex for which all fuel descriptors required for the solution of the Rothermel (1972) mathematical rate of spread model are specified.

Favorable evaluations of observed versus predicted rate of surface fire spread have been obtained with the Rothermel model in a number of fuel complexes (Cruz and Alexander 2013). Rothermel acknowledged that his model was not applicable to predicting the behavior of crown fires because the nature and mechanisms of heat transfer between the two types of spread regimes were quite different. Later on, he did offer advice on judging whether crowning was possible or not based on the surface fire's predicted intensity or flame length (Rothermel 1983). In turn, crown fire spread rates were assumed to be two to four times the predicted surface fire rate of spread in the Anderson (1982) fire behavior fuel model in litter and understory.

Rothermel (1991) eventually produced a guide for predicting crown fire behavior in the northern Rocky Mountains of the United States and areas with similar fuels and climate. The core component of his method was a simple correlation derived from eight observations of crown fire rate of spread versus the corresponding predictions from his surface fire rate of spread model. He emphasized that his statistical model (incorporating a multiplier of 3.34) for predicting the spread rate of wind-driven crown fires was a first approximation and that more research was needed to strengthen the analysis.

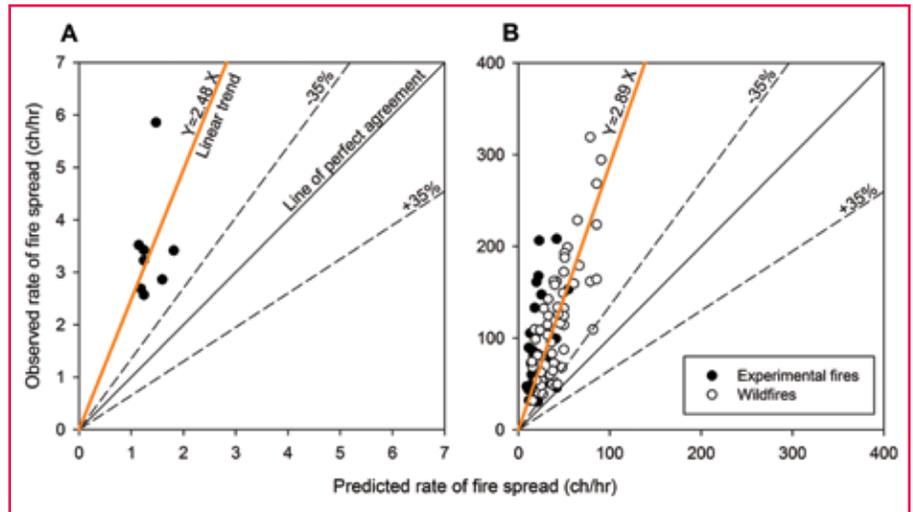


Figure 1.—Observed head fire rates of spread associated with (A) experimental surface fires ($n = 8$) in lodgepole pine forests in central British Columbia by Lawson (1972) versus predictions based on the Rothermel (1972) surface fire rate of spread model and (B) a dataset of experimental crown fires ($n = 34$), and crowning wildfires ($n = 54$) in various conifer forest types compiled by Cruz and Alexander (2010) versus predictions based on the Rothermel (1991) crown fire rate of spread model. The dashed lines around the line of perfect agreement indicate the ± 35 percent error interval.

Just How Predictable Is Wildland Rate of Fire Spread?

Cruz and Alexander (2013) examined the limits of predictability in surface and crown rate of fire spread from a compilation of 49 model evaluation datasets containing 1,278 observations in 7 different fuel type groups from various regions of the world. They reached the following conclusions:

- Only 3 percent of the predictions (35 out of 1,278) were considered to be “exact” predictions: undeniably, an elusive target.
- The mean percent error varied between 20 and 310 percent and was homogeneous across fuel type groups.
- Slightly more than half of the evaluation datasets had mean errors between 51 and 75 percent.
- Underprediction bias was prevalent in 75 percent of the 49 datasets analyzed.
- A case was made for suggesting that a ± 35 -percent error interval

would constitute a reasonable standard for model performance in predicting a wildland fire’s forward or heading rate of spread.

- Empirical-based fire behavior models developed from a solid foundation of field observations and well-accepted functional forms adequately predicted rates of fire spread far outside of the bounds of the original dataset used in their development.
- The prediction of surface fire rate of spread was found to be more difficult than predicting the rate of spread of crown fires, a result of the larger influence of fuel structure on low-intensity fire propagation.

Point and Landscape-Scale Fire Behavior Modeling Systems in the United States

Since the late 1990s, a number of computerized decision-support systems—such as BehavePlus, NEXUS, the Fire and Fuels Extension to the Forest Vegetation Simulator, FARSITE, FlamMap,

Fuel Management Analyst Plus, ArcFuels, and the Wildland Fire Decision Support System—either have been separately implemented or linked Rothermel’s surface and crown rate of fire spread models (1972, 1991) with Van Wagner’s (1977) crown fire transition and propagation criteria. These systems are extensively used for fire operations, planning, and research.

In spite of the popularity of these fire behavior modeling systems over the years, some user-oriented problems have emerged. Varner and Keyes (2009) have, for example, identified several commonly encountered errors in regards to the modeling inputs:

- Live and dead fuel moisture estimation,
- Wind adjustment factors,
- Fuel load estimates,
- Fuel model selection,
- Fuel decomposition rates, and
- Fuelbed patchiness.

They suggested that the errors “can often be tied to unsupported assumptions about actual conditions and overreliance on default values.”

Cruz and Alexander (2010) have also pointed out that the operational fire behavior modeling systems currently used to simulate the onset of crowning and active crown fire rate of spread in conifer forests of the Western United States exhibit a significant underprediction bias related to several factors, including:

- Incompatible model linkages.
- Use of surface and crown fire rate of spread models that have inherent underprediction biases themselves (figure 1). The underprediction tendency with

the Rothermel (1991) model was also found to occur with the Schaaf and others (2007) crown fire rate of spread model of the fuel characteristic classification system.

- A reduction in crown fire rate of spread based on the use of unsubstantiated functions for crown fraction burned (that is, a measure of the degree of crown fuel consumption expressed as a percentage of the total number of tree crowns and, as such, constituting an indication of the

probable type of fire activity to be expressed over a burned area for fuel types that are susceptible to crowning).

The use of uncalibrated custom fuel models to represent surface fuelbeds was considered as a fourth potential source of bias. Ager and others (2011) claim that such limitations “are well known by the user community” but offered no empirical evidence to substantiate their statement.

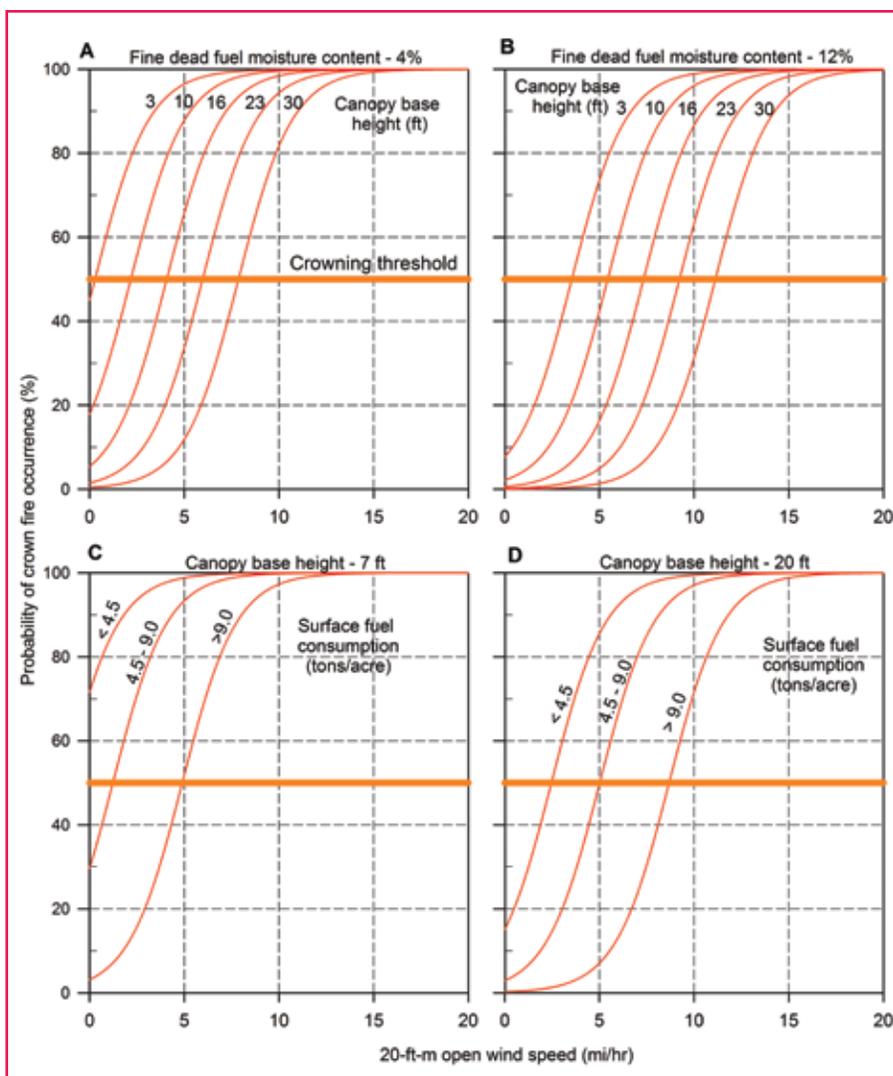


Figure 2.—The likelihood of crown fire occurrence as (A-B) a function of canopy base height and wind speed for two fine dead fuel moisture levels assuming a surface fuel consumption of 4.5 to 9.0 tons/acre, and (C-D) as a function of surface fuel consumption and wind speed assuming a fine dead fuel moisture of 4 percent (after Alexander and Cruz 2013). The solid horizontal line in each graph represents the approximate threshold value for the onset of crowning (0.5 probability of crown fire occurrence).

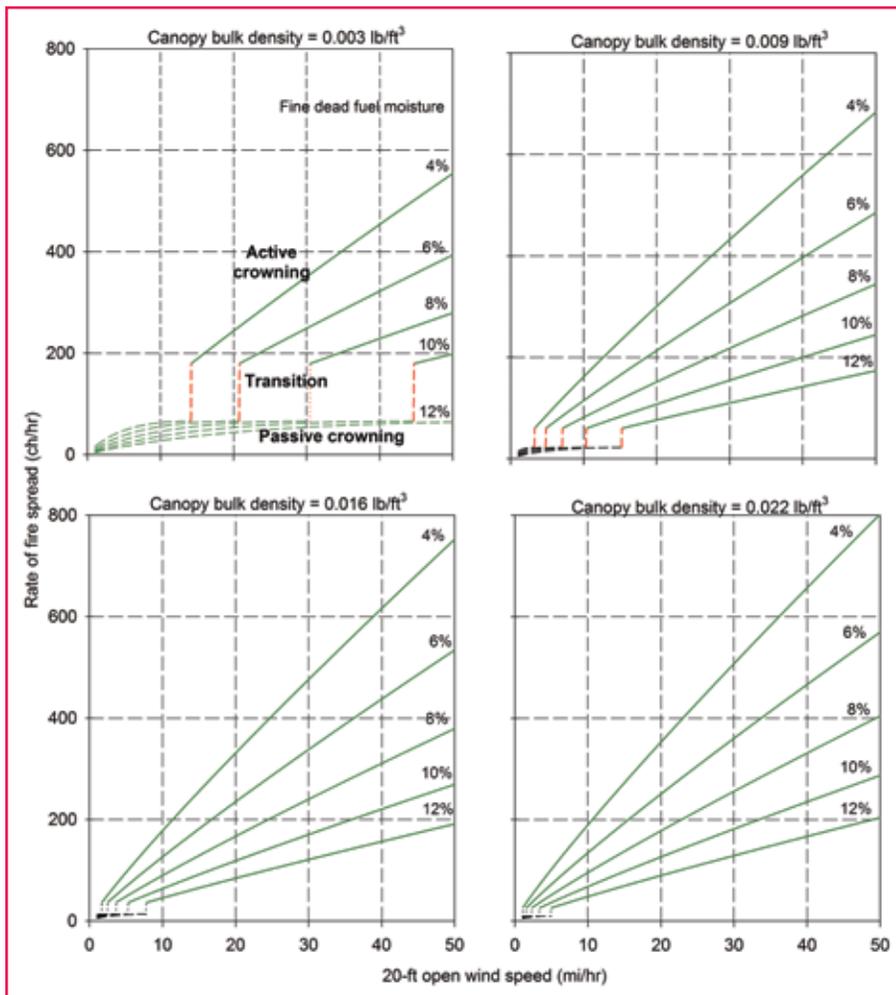


Figure 3.—Passive and active crown fire spread rates as a function of wind speed and fine dead fuel moisture for four canopy bulk density levels (after Alexander and Cruz 2013). The vertical “kinks” in the fine dead fuel moisture curves are considered to represent the wind speed thresholds between passive and active crowning.

The Canadian System of Fire Behavior Prediction

The Canadian Forest Fire Behavior Prediction system (FBP) (Wotton

and others 2009) is a module of the larger Canadian forest fire danger rating system (<http://www.frames.gov/cffdrs>), which also includes the Canadian Forest Fire Weather Index (FWI). The FBP is used in parts of

the United States—specifically, in the Lake States and Alaska, where conifer forests are structurally similar to those found in Canada. Eleven of the 16 fuel types included in the FBP are subject to crowning (seven coniferous and four mixed-wood forest stand types). Parts of the system are also used outside of North American—for example, in New Zealand (Pearce and others 2012).

The FBP is similar in many respects to the fire behavior modeling systems currently used in the United States. The principal difference lies in its technical basis. While the Rothermel (1972) surface fire model is based largely on laboratory fires and physical theory, the FBP system is empirical in nature, based on the analysis of experimental fires and observations of wildfires dating back about 50 years (Stocks and others 2004).

The Crown Fire Initiation and Spread System

The Crown Fire Initiation and Spread (CFIS) software system is a suite of empirically based models for predicting crown fire behavior (Alexander and others 2006) based largely on a reanalysis of the experimental fires carried out in conifer forest fuel types used in the development of the Canadian FBP System.

Words of Wisdom†

“Anyone can tell what a fire has done, and most can look at a fire and tell what it is doing—but your challenge to be successful and survive in fighting wildfire is to be able to correctly predict what the fire will do, well before it does it.... Pay attention to the signs the smoke is always giving: color, intensity, pulsing or steady, and direction of drift. Pay special attention to the fuels it’s getting into and the topography that will influence its behavior. Constantly monitor the weather’s relative humidity, temperature, and especially the winds.”—

Earl Cooley (1967)

†From Trembath (2011), describing the advice offered by a veteran smokejumper regarding fire behavior during a training session in his first season of wildland firefighting as a member of the Flathead Hotshots based out of northwestern Montana.

Table 1.—Predicted fine dead fuel moisture content as a function of ambient air temperature and relative humidity assuming >50 percent shading at between 1200–1600 hours during May–July on level terrain (adapted from Rothermel 1983).

| Relative humidity (%) | Air temperature (°F) | | | | |
|-----------------------|-----------------------------|---------|---------|----------|------|
| | 32 – 49 | 50 – 68 | 69 – 88 | 89 – 108 | >109 |
| | Fine dead fuel moisture (%) | | | | |
| 0 – 4 | 4 | 4 | 4 | 4 | 4 |
| 5 – 9 | 5 | 5 | 4 | 4 | 4 |
| 10 – 14 | 5 | 5 | 5 | 5 | 5 |
| 15 – 19 | 6 | 6 | 5 | 5 | 5 |
| 20 – 24 | 7 | 7 | 6 | 6 | 6 |
| 25 – 29 | 8 | 8 | 7 | 7 | 7 |
| 30 – 34 | 8 | 8 | 8 | 7 | 7 |
| 35 – 39 | 9 | 9 | 8 | 8 | 8 |
| 40 – 44 | 10 | 9 | 9 | 9 | 9 |
| 45 – 49 | 10 | 10 | 10 | 10 | 10 |
| 50 – 54 | 10 | 10 | 10 | 10 | 10 |
| 55 – 59 | 11 | 11 | 11 | 11 | 11 |
| 60 – 64 | 12 | 11 | 11 | 11 | 11 |
| 65 – 69 | 12 | 12 | 11 | 11 | 11 |
| 70 – 74 | 13 | 12 | 12 | 12 | 12 |
| 75 – 79 | 14 | 13 | 13 | 13 | 13 |

The primary models incorporated into CFIS have been evaluated against both outdoor experimental fires and wildfire observations and shown to be reasonably reliable. The two main outputs of CFIS are:

- Likelihood of crown fire initiation or occurrence based on two distinct approaches: the canopy base height and/or certain components of the Canadian FWI or the fine dead fuel moisture, canopy base height or fuel strata gap, wind speed, and an estimate of surface fuel consumption (figure 2).

- Type of crown fire (passive crown fire or active crown fire) according to Van Wagner’s (1977) criterion for active crowning and its associated rate of spread based on fine dead fuel moisture, canopy bulk density, and wind speed (figure 3).

The estimation of the fine dead fuel moisture input in CFIS follows Rothermel’s (1983) tabular method (table 1). In lieu of a weather station measurement or a forecasted value, the 20-foot (6.1 m) open wind speed input can be estimated in the field using the Beaufort

wind scale (see figure 4). CFIS is available for downloading free at <<http://www.frames.gov/partnersites/applied-fire-behavior/cfis/>>.

Final Thoughts on Predicting Crown Fire Behavior

Models or guides that have a good fundamental framework and a solid empirical basis presumably predict fire behavior well when used for conditions that are within the database parameters used in their development. An understanding of the uncertainty inherent in fire behavior predictions should always accompany the process of conducting and communicating fire simulations. An overestimate can easily be readjusted without serious repercussions; however, an underestimate of fire behavior can be disastrous both for fire operations and the credibility of the person making the prediction (Cheney 1981). The underprediction trends in both surface and crown fire behavior noted earlier on with respect to the U.S. fire behavior models and modeling systems should be of concern to users.

Acknowledgment

Thanks to Charley Martin (U.S. Geological Survey) for his comments.

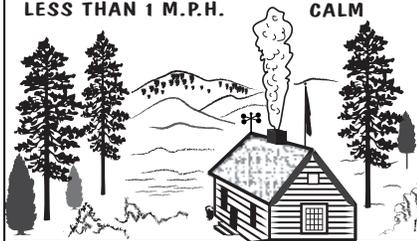
NORTHERN ROCKY MOUNTAIN SCALE OF WIND VELOCITY

FOR USE IN ESTIMATING WIND VELOCITIES IN WESTERN MONTANA AND NORTHERN IDAHO

NORTHERN ROCKY MOUNTAIN FOREST • RANGE EXPERIMENT STATION

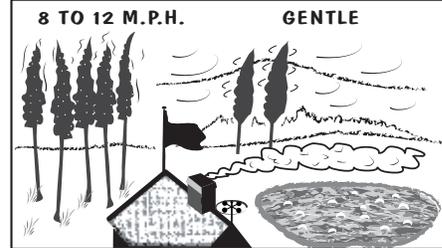
WIND CLASS TERMS USED IN U.S.W.B. FORECASTS EFFECTS OF WIND

LESS THAN 1 M.P.H. CALM



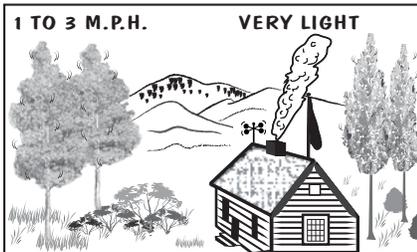
SMOKE RISES VERTICALLY; NO MOVEMENT OF LEAVES OF BUSHES OR TREES.

8 TO 12 M.P.H. GENTLE



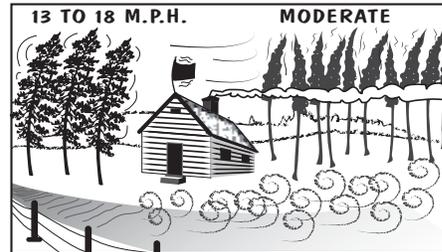
TREES OF POLE SIZE IN THE OPEN SWAY VERY NOTICEABLY; LARGE BRANCHES OF POLE-SIZE TREES IN THE OPEN TOSS; TOPS OF TREES IN DENSE STANDS SWAY; WIND EXTENDS SMALL FLAG; A FEW CRESTED WAVES FORM ON LAKES.

1 TO 3 M.P.H. VERY LIGHT



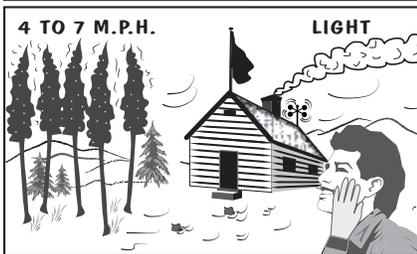
LEAVES OF QUAKING ASPEN IN CONSTANT MOTION; SMALL BRANCHES OF BUSHES SWAY; SLENDER BRANCHLETS AND TWIGS OF TREES MOVE GENTLY; TALL GRASSES AND WEEDS SWAY AND BEND WITH WIND; AND VANE BARELY MOVES.

13 TO 18 M.P.H. MODERATE



TREES OF POLE SIZE IN THE OPEN SWAY VIOLENTLY; WHOLE TREES IN DENSE STANDS SWAY NOTICEABLY; DUST IS RAISED IN ROAD.

4 TO 7 M.P.H. LIGHT



TREES OF POLE SIZE IN THE OPEN SWAY GENTLY; WIND FELT DISTINCTLY ON FACE; LOOSE SCRAPS OF PAPER MOVE; WIND FLUTTERS SMALL FLAG.

19 TO 24 M.P.H. FRESH



BRANCHLETS ARE BROKEN FROM TREES; INCONVENIENCE IS FELT IN WALKING AGAINST WIND.

25 TO 38 M.P.H. STRONG



TREES ARE SEVERELY DAMAGED BY BREAKING OF TOPS AND BRANCHES; PROGRESS IS IMPEDED WHEN WALKING AGAINST WIND; STRUCTURAL DAMAGE; SHINGLES ARE BLOWN OFF.

The Beaufort scale for estimating 20-foot (6.1 m) open wind speeds when instruments are not available or appropriate for measurement (from Gisborne 1941).

Can Crown Fire Behavior in Mountain Pine Beetle-Attacked Stands Be Modeled Using Operational Models?

Assessing crown fire potential in mountain pine beetle (MPB)-attacked conifer forests is a topical subject (Page and others 2013a). Several authors applied operational fire behavior modeling systems (such as BehavePlus, the Fire and Fuels Extension to the Forest Vegetation Simulator, and NEXUS) to lodgepole pine forests attacked by MPB in the past couple of years (Page and others, in review). It is unknown how appropriate the crown fire behavior components of these systems are to the “red” and “gray” stages of MPB-attacked

forests. Page and others (2013b) recently documented foliar moisture contents as low as ~7 percent in the red stage of MPB attack on lodgepole pine trees.

Given the empirical basis of Van Wagner’s (1977) criteria for crown fire initiation (that is, live conifer forests with foliar moisture contents in and around 95 to 135 percent), this is a situation for which the operational fire behavior modeling systems never were designed (Page and others in review) and could possibly result in erroneous outcomes.

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CAPTURING CROWN FIRE BEHAVIOR ON WILDLAND FIRES—THE FIRE BEHAVIOR ASSESSMENT TEAM IN ACTION



Nicole M. Vaillant, Carol M. Ewell, and Josephine A. Fites-Kaufman

The ability to understand and predict fire behavior is important for a number of fire management activities, such as planning effective fuel reduction treatments, designing fire-resilient landscapes near the wildland-urban interface, planning and managing prescribed fires, providing for firefighter safety, and supporting wildland fire operations. Fire behavior models have been developed to predict the occurrence and characteristics of surface and crown fire behavior based on laboratory data (Rothermel 1972, Viegas 2004), outdoor experimental fires (Stocks and others 2004), and wildfire observations (Rothermel 1991).

Quantitative measurements of free-burning wildland fires are important to the validation and further development of fire behavior prediction models (Lentile and others 2007, Ottmar 2011). Laboratory and experimental fires cannot replicate many of the scale-dependent fire behavior characteristics that occur on wildland fires in larger, complex landscapes involving the interactions of fire with variable topography, weather, and atmospheric conditions.

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The International Crown Fire Modeling Experiment (ICFME) (Stocks and others 2004) and FROSTFIRE (Hinzman and others 2003) are examples of high-intensity, field-scale fire experiments that provided valuable information of fire behavior. Nonetheless, these experiments still cannot replicate some of the conditions that are found in free-burning wildland fires.

While still not perfect, advancements in technology have made it possible to gather fire behavior data on actively burning wildland fires (Butler and others 2010, Jimenez and others 2007). The Adaptive Management Services Enterprise Team (AMSET: a subunit of the Forest Service) formed the Fire

Behavior Assessment Team (FBAT) to gather such detailed fire behavior data.

FBAT is a unique team that specializes in measuring fire behavior on prescribed burns and wildland fires. FBAT includes 6 to 12 qualified fire-line employees with at least 1 crew boss or (more typically) 1 division supervisor. The primary team goals are to (1) measure fire behavior and effects and their relationships to prefire fuels, fire history, and treatments; (2) measure fire effects on archeological and biological values; and (3) build a dataset useful for calibration of consumption, smoke production, and fire behavior models. FBAT also actively collaborates and shares data with interested land managers and research groups.

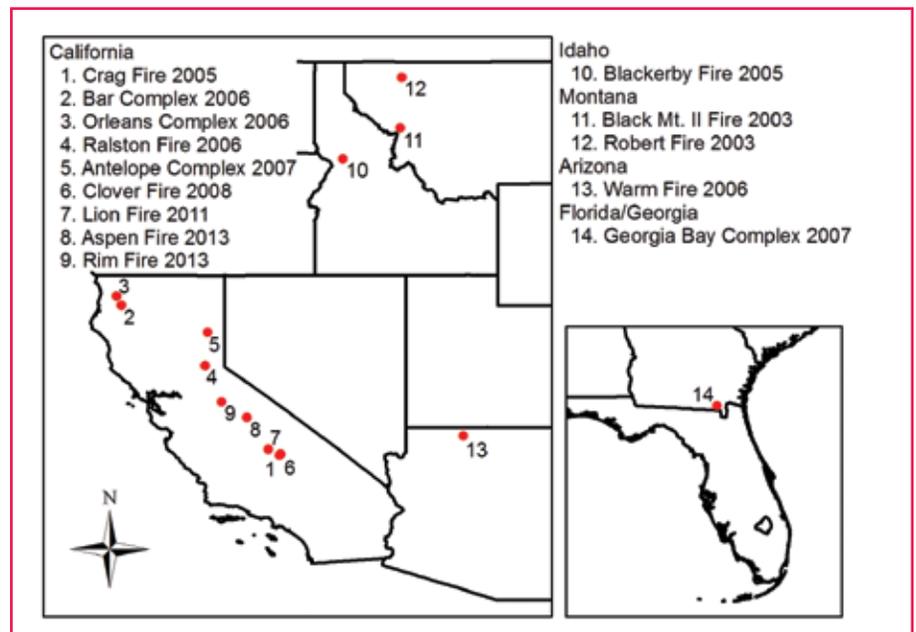


Figure 1.—Location of all the wildland fires where data has been collected from 2003 through 2013 by the Fire Behavior Assessment Team.

A Brief History— Chasing Fires

Created in 2002, FBAT (initially called the Rapid Response Team) worked closely with personnel at the Forest Service's Missoula Fire Lab and Missoula Technology and Development Center to build equipment to monitor and measure fire behavior. The team initially tested the equipment in the Wolf Wildland Fire Use Fire project in Yosemite National Park in 2002.

Since its inception, FBAT has collected weather, fuels, and fire behavior data from 14 wildland fires (figure 1) and several operational and experimental prescribed burns. In addition, FBAT members have visited numerous other wildland fires. At these fires, however, FBAT members did not collect data because of monitoring issues, such as access, safety, or fire progression; team members arrived after the fire was brought under control; or the fire did not reach the monitoring sites.

Monitored fire behavior ranged from slow backing flame fronts to active crown fire runs. A number of so-called extreme fire behavior features were captured in video footage, including fire whirls, ember and firebrand ignition of spot fires, coalescence of spot fires, and merger of such spot fires with the main flame front. Complete data was gathered on a total of 98 sites burned by wildland fire and 32 sites within prescribed fires, including research burns.

Data Collection

Once deployed on a wildland fire incident, FBAT works within the incident management system for safety and updates regarding fire behavior and operation plans. In coordination with the division

supervisor, the team then determines where to set up the equipment near the active fire edge and gather fuels data. Site selection takes into account the weather forecast and likelihood of an area burning, yet offering safe access and egress for FBAT. Each selected site takes about an hour to set up fire behavior equipment and perform a fuels inventory (figure 2). Over the years, fire behavior equipment has been modified and upgraded—for example, to include an anemometer and dual heat flux sensors—as a result of input from both operations and research personnel.

Fire Behavior Equipment

Video camera. FBAT sets up one or two video cameras in stainless steel, fire-resistant boxes. The camera is started by a trigger connected to a network of wires and thermistors. When any of the wires are burned through by the fire, the camera is switched. Each camera contains a digital videotape that can record 80 minutes of footage.

In the view of each camera are three photo reference markers (the poles in figure 2) at a known distance from the camera and painted in 1-foot (0.3-m) increments to aid in estimating flame dimensions. These markers, added in 2006, are also used to estimate rate of spread of the fire.

Temperature sensors (thermocouples). Type K thermocouple sensors are connected to data loggers to collect detailed flame temperature data. These sensors are installed at different heights on a pole. Individual thermocouples are also set up in a diamond pattern and attached to smaller data loggers buried in stainless steel canisters. The pattern (with the poles at its center) creates eight defined triangles, enabling calculation of the rate of spread and direction of the flame front (Simard and others 1982).

Heat flux sensor. Heat flux is measured through a dual sensor containing both a radiometer and total heat flux transducer. Convective heat flux is computed from the dif-

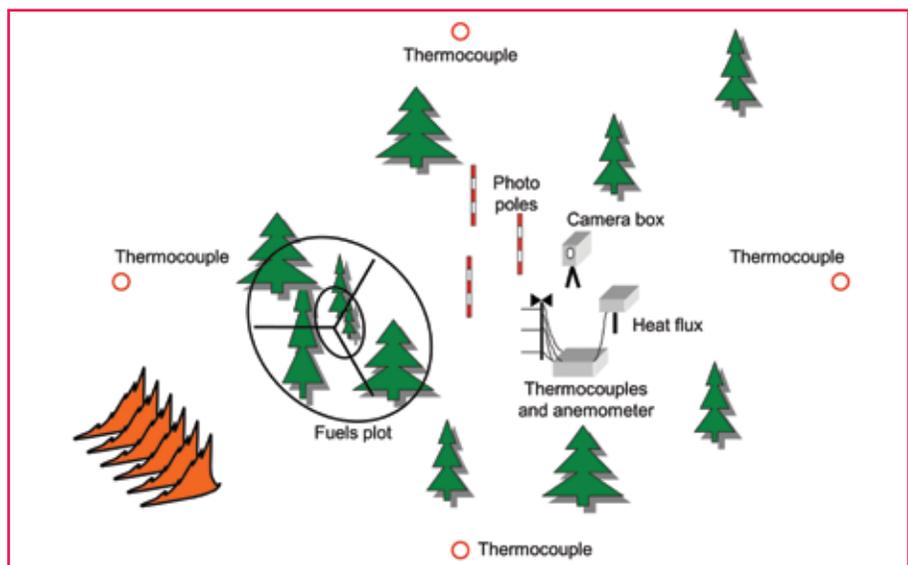


Figure 2.—Site schematic with the typical site orientation based on predicted fire behavior. Each site includes both fire behavior equipment (camera, anemometer, and thermocouples) and a fuels inventory plot. Schematic is not drawn to scale.

ference between the measured total and radiant heat fluxes. These sensors are connected to the same data logger as the vertically mounted thermocouples.

Anemometer. An anemometer was added to the equipment setup in 2007 to capture site-specific winds to augment fire behavior measurements. The anemometer captures the 10-second average wind speed at about 4.5 feet (1.4 m) above ground surface. The anemometer is constructed of plastic cups, so wind data is only collected prior to arrival of the flame front, which often melts the cups. Wind direction estimates were later added to the data from video of noncombustible flagging attached to the photo poles. Anemometer data is logged in the same data logging system collecting thermocouple and heat flux data.

Fuels Inventory

Fuels are inventoried prior to and after the flame front passage through an instrumented site. Surface and ground fuels are inventoried with one to three planar fuel transects (Brown 1974). Understory vegetation (seedlings, shrubs, grasses, and forbs) is estimated using type and density categories (Burgan and Rothermel 1984). Two variable radius prism plots are established for pole-sized and overstory trees in which species, vigor, diameter, height to crown base, and total tree height are recorded. Afterward, stand structure calculations are completed using the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Crookston and Dixon 2005, Rebain 2010). Fuel samples are collected to estimate litter, dead woody, and live vegetation fuel moisture (including foliar moisture content). Postfire measurements include char, scorch,



(A) Members of the Fire Behavior Assessment Team setting up the fire-resistant video cameras and radiant heat flux sensor on the Crag Fire in 2005 (photo: Rosalind Wu, Forest Service) and (B) gathering fuels data near the anemometer on the Georgia Bay Complex in 2007 (photo courtesy of Adaptive Management Services Enterprise Team).

and torch heights for each tree. Sampling methods are added when a change in vegetation type warrants or if local units are interested in monitoring the effect of fire on specific plant species.

Black Mountain II Fire Case Study: Crown Fire Behavior Captured

The Black Mountain II Fire on the Lolo National Forest in Montana was started on August 8, 2003, by lightning. The fire was contained at 7,061 acres (2,857 ha) and exhibited mixed severity, from low-intensity surface fire to active crown fire. The fire exhibited active crown fire prior to the arrival of FBAT, including a 5-mile (8-km) run. The first round of sites installed by FBAT did not burn. In the second monitoring attempt, FBAT collected data on two adjacent sites on the upper-third portion of a steep (50–55 percent grade), northeast-facing slope. At one site, the vegetation was predominantly dense Douglas-fir (*Pseudotsuga menziesii*) forest with scattered individuals or patches of open ponderosa pine (*Pinus ponderosa*) forest; the second site was predominately open ponderosa pine forest. These sites are hereafter referred to as the “dense” and “open” sites, respectively. The fire reached the sites in the afternoon

of August 21 at approximately 3:20 p.m.

Prefire Site Characteristics

Tree density was 469 trees/acre (1,159 trees/ha) in the dense site and 294 trees/acre (726 trees/ha) in the open site. Estimated canopy bulk densities were 0.018 pounds (lb) per cubic feet (ft³) (0.29 kg/m³) on the dense site and 0.007 lb/ft³ (0.12 kg/m³) on the open site. Canopy base height was 19.7 feet (6.0 m) and 7.9 feet (2.4 m) on the dense and open sites, respectively. Fine fuel load (litter, 1-hour dead-down woody debris, and live herbaceous and woody fuels) was higher in the dense site—37 tons/acre (83 t/ha)—than the open site—14 tons/acre (32 t/ha). Likewise, total fuel load (the sum of ground, surface, and live fuels) was 106 tons/acre (237 t/ha) for the dense site and 62 tons/acre (139 t/ha) for the open site.

Weather and Fuel Moisture Conditions

Between 3:00 and 4:00 p.m., at the nearby ridgetop weather station, 20-foot (6.1 m) open winds reached no more than 2 to 7 miles/hr (3 to 11 km/hr) and averaged less than 1 mile/hr (1.5 km/hr). The temperature was 73 °F (23 °C) and relative humidity was 20 percent. Onsite fuel moistures from the late morn-

ing were 70 to 87 percent for foliage of the lower branches of conifer trees, 50 to 72 percent for the shrubs, and between 4 and 7 percent for litter and arboreal lichens.

Observed Fire Behavior

At each site, FBAT measured or inferred several fire behavior characteristics. All ground, surface, understory vegetation, and fine canopy fuels were consumed on both the dense and open sites. Video images showed a solid “wall” of flame from the surface up through the canopy, indicative of an active crown fire. The estimated rate of spread was almost three times faster in the dense site—188–215 chains/hour (63–72 m/min)—

than the open site—69–81 chains/hour (23–27m/min). Temperatures exceeded the manufacturer’s short-term heat ratings for the thermocouples—1,800 °F (982 °C)—at the dense site and peaked at 1,112 °F (600 °C) at the open site.

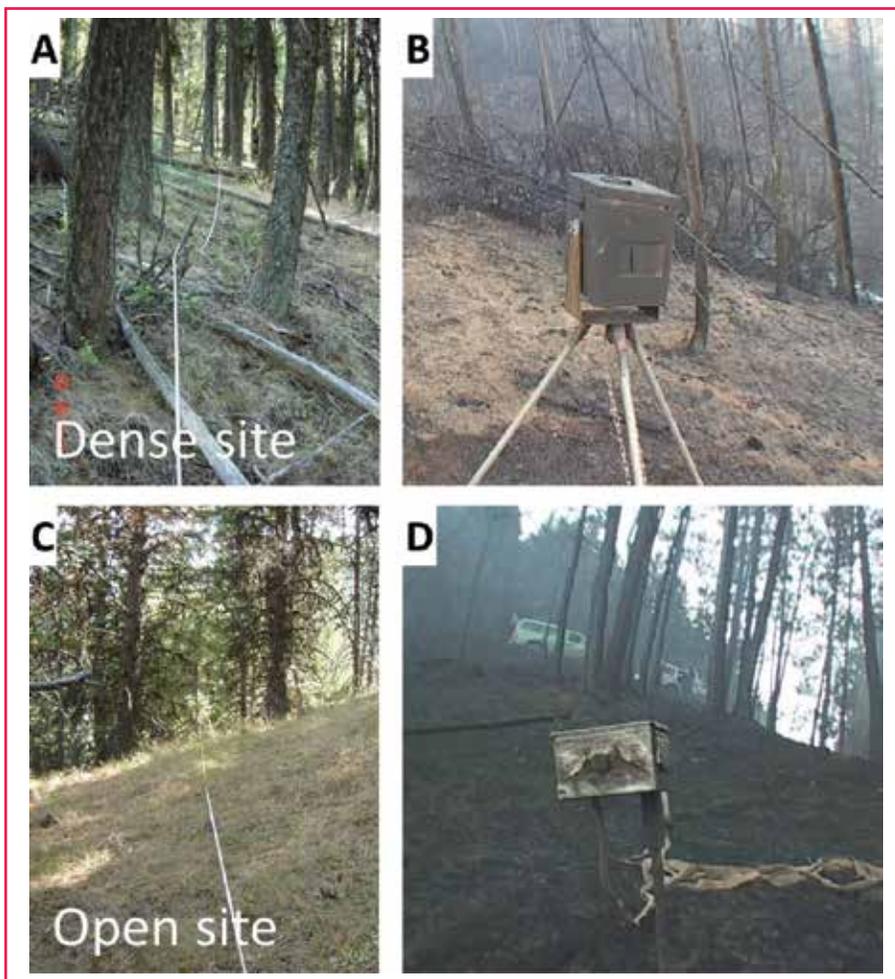
Lessons Learned/ Working Into the Future

Installing complex sensors and making fuel measurements ahead of an actively burning wildland fire is incredibly difficult. Yet, the fire behavior data gained on free-burning, active wildfires cannot be collected in any other way. Over 11 years of data collection by FBAT, many valuable lessons have been

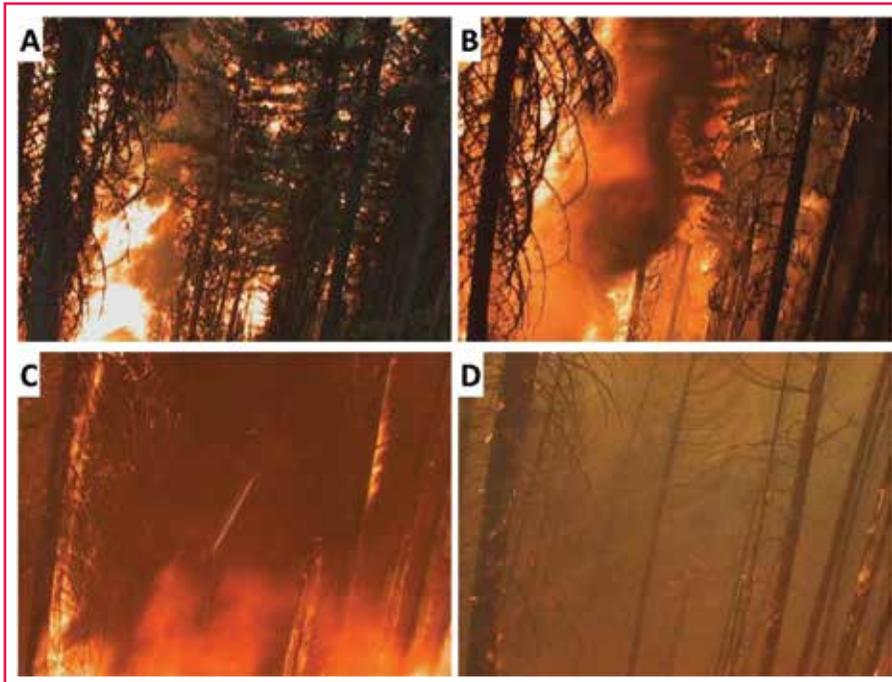
learned about equipment needs and sampling protocols. Continued refinement and addition of data collection and sensors makes the data that much more valuable. The inclusion of the poles for future video analysis, the anemometer for site-specific winds, and the addition of the rate of spread sensors are all enhancements to the original video-camera equipment.

Challenges abound, and equipment survivability has been a central issue. Equipment will likely fail at a certain point in time because of high temperatures associated with intense fire; however, keeping the failures to a minimum is a goal. Although natural fuel configuration at the monitoring site ideally should be retained for data accuracy, some clearing is needed to prevent equipment loss: if the equipment is lost, there is no data collected to offset the loss. Procedures now include clearing large fuels around the data boxes and burying the boxes deeper.

High-intensity wildfires in coniferous systems appear to be occurring more frequently and are burning more area than ever before. In order to better understand and predict wildfire behavior, there is a need to continue this type of work. FBAT will continue to refine and adapt data collection methodologies to better capture data that is meaningful and useful for both researchers and practitioners by improving existing and future fire behavior modeling systems, validating fuel consumption models to predict fire effects and smoke production, and relating fire behavior to initial and long-term fire effects. In addition, FBAT is creating a valuable archive of video images that can be used for training in fire safety, human factors, and sociological applications.



Prefire (A and C) and postfire (B and D) photos of the dense and open sites monitored on the Black Mountain II Fire. Photos courtesy of Adaptive Management Services Enterprise Team.



Time series photos from a fire-resistant video camera during the Black Mountain II Fire in Montana in 2003 as the active crown fire passed the camera in the dense site. Photos courtesy of Adaptive Management Services Enterprise Team.

How Can You Work With FBAT?

FBAT is available to gather data on wildfires as well as prescribed fires. Deployment is ordered via the National Interagency Resource Ordering and Status System. For instance, FBAT began a partnership with two wildland fire modules on the Stanislaus National Forest in California in the summer of 2013. For more information about working with FBAT, contact Carol Ewell (cewell@fs.fed.us). For more information about FBAT and past fire reports, visit <<http://www.fs.fed.us/adaptivemanagement/projects/FBAT/FBAT.shtml>>.

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TOWARD IMPROVING OUR APPLICATION AND UNDERSTANDING OF CROWN FIRE BEHAVIOR

Martin E. Alexander, Miguel G. Cruz, and Nicole M. Vaillant



The suggestion has been made that most wildland fire operations personnel base their expectations of how a fire will behave largely on experience and, to a lesser extent, on guides to predicting fire behavior (Burrows 1984). Experienced judgment is certainly needed in any assessment of wildland fire potential but it does have its limitations. The same can be said for mathematical models and computerized decision-support systems. Case history knowledge will prove a useful complement to fire behavior modeling and experienced judgment when it comes to appraising potential fire behavior (Alexander and others 2013b). Weighing each type of input in predicting wildland fire behavior is vital and yet is as much an art as a science.

The Continued Role of Wildland Fire Research

Wildland fire research has done much to contribute to our current understanding of the behavior of crowning forest fires through laboratory experiments, outdoor

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experimental burning, numerical modeling, and wildfire case histories. Presumably, the future holds similar promise, provided we are readily willing to admit what we still do not know about crown fires with respect to their environment, characteristics, and prediction. Several major research needs were in fact identified during a recent synthesis of knowledge on crown fire behavior (Alexander and others 2013a).

While basic research into fire fundamentals is essential to understanding the physical processes involved in crown fire dynamics, traditional scientific study and evaluating model performance are necessary to develop a complete picture of crown fire dynamics (Alexander and Cruz 2013). As new models are developed, model com-

ponents (such as built-in functional forms, heat transfer processes, and sensitivity to environmental variables) must undergo the same robust evaluation as model outputs (such as rate of fire spread, flame depth, and flame height).

Wildfire Behavior Monitoring and Documentation Needs

There have been recent attempts to monitor and document the behavior of high-intensity crown fires (Alexander and Thomas 2003a, 2003b). Earlier efforts by fire researchers and fire meteorologists in various regions of the United States in the 1950s and 1960s were, for the most part, not sustained beyond the early 1970s (figure 1). Some efforts are now being made to monitor and document wildfire



The mobile fire laboratory used by the fire behavior documentation team of the Forest Service, Southern Forest Fire Laboratory, Macon, GA, on wildfires and prescribed fires during the 1960s and 1970s. Photo courtesy of Dale D. Wade, Forest Service (retired).

behavior—for example, by the Fire Behavior Assessment Team described in another article in this issue and by the Texas Forest Service, which has recently completed a number of wildland-urban interface case studies (Ridenour and others 2012).

Regretably, valuable information and insights into free-burning wildland fire behavior are not being captured in a systematic way. Consider for the moment that there is no quantitative data on rate of spread obtained from wildfires or prescribed fires by which to assess the accuracy of physics-based models used to simulate fire behavior in mountain pine beetle-attacked forests (Hoffman and others 2013, Linn and others 2013).

Less than a tenth of 1 percent of all wildfires is documented in a case study or history report. What is required is a permanently staffed, ongoing effort to do so. Alexander (2002) suggested that there is a need to create operational fire behavior research units specifically for this purpose. Recent advances in all aspects of the technology—communications, photography, weather observations, remote sensing, and infrared mapping, including the use of unmanned drones—associated with monitoring and documenting high-intensity wildfires have gradually made that task easier (Cruz and others 2012).

Such observation and documentation of crown fire behavior is crucial to evaluating new and existing predictive models of crown fire behavior (Holcomb and Rogers 2009, WDNR 2005). The completion of case histories on wildfires and prescribed fires is not strictly the domain of fire research; such a task should be regarded as a shared responsibility between wildland fire researchers and fire management personnel as part and parcel of adaptive management. Efforts to foster a culture within the wildland fire community that embraces the value of case histories is sorely needed.

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Past Efforts of Monitoring Wildfire Behavior in Conifer Forests

1957 Pond Pine Fire, North Carolina (adapted from U.S. Department of Agriculture 1958)

The so-called Pond Pine Fire started in Tyrrell County, North Carolina, in a flat, swampy, organic soil area and burned an estimated 5,000 acres [2,205 ha] during an 8-hour period following 2:00 p.m. on May 9, 1957. Although surface fuels were fairly dry, neither the buildup nor burning indexes were considered critical; the same was true of relative humidity and surface winds. In short, there was little on the surface to indicate that such an explosive, high-intensity fire would develop.

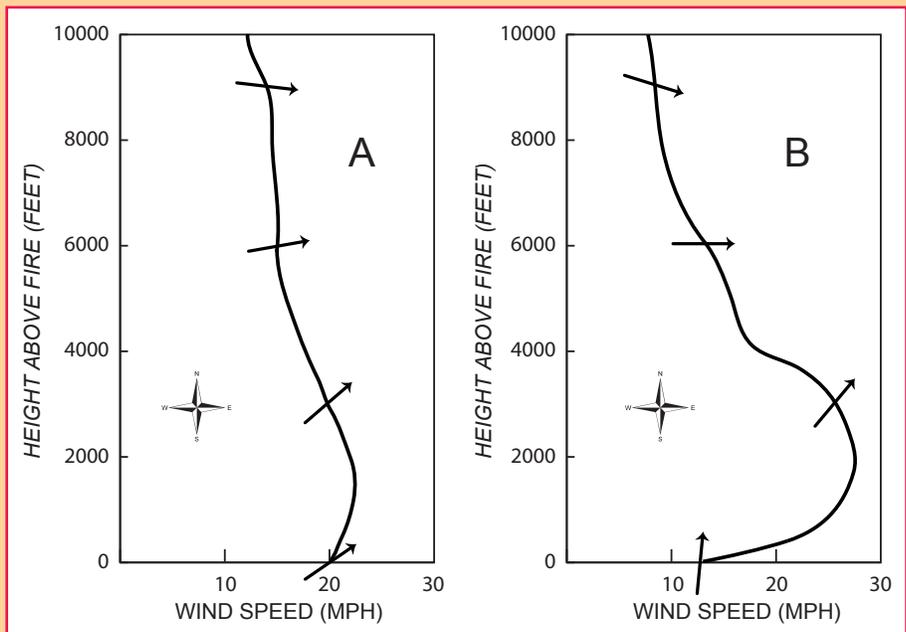
The fire started at 10:45 a.m. and early on had a tendency to generate spot fires for short distances ahead of the flame front. About 2 hours later, backfires were started from highways, but before they could burn an effective distance, the main head spotted for several hundred feet beyond one of the highways. A strong convection column then developed. At about 4:15 p.m., the fiercely burning fire spotted across a second highway and continued as a firestorm at a rate of 5 miles [8 km] in 3 hours. According to a plane observer, the head reached maximum intensity at about 5 o'clock. At that time, spot fires were being set as much as 3/4 mile [1.2 km] ahead of the main front. The con-

vection column was of the towering type, with a white condensation cap. The height to the base of the cap was estimated at 4,600 feet [1,400 m] and to the top, 7,300 feet [2,225 m]. At about 10:00 p.m., a backfire and high relative humidity stopped the head.

The unusual characteristics of the fire can most reasonably be explained on the basis of winds aloft. Three U.S. Weather Bureau Stations (Raleigh and Cape Hatteras, NC, and Norfolk, VA) form a triangle, with the fire area roughly at its center. As soundings on May 9 at all three stations agreed closely as to high-altitude

wind velocity and direction profiles, it seemed safe to assume that the same conditions prevailed over the fire. A composite of upper air soundings from the three stations indicated a dangerous wind profile, with a low-level jet stream and decreasing winds aloft highly conducive to the formation of a strong convection column—conductive to long-distance spotting of firebrands.

The Pond Pine Fire is another in a growing list of case histories that strengthen the concepts that were originally advanced several years ago regarding the significance of the wind profile in blowup fires.



Estimated wind profile curves in the vicinity of the Pond Pine Fire on May 9, 1957. The curves are composites of the upper air soundings from Raleigh and Cape Hatteras, NC, and Norfolk, VA. Composite wind directions aloft are indicated by the arrows; (A) represents conditions at 3:30 p.m. and (B) at 9:30 p.m.

1958 Coal Creek Fire, Montana (adapted from USDA Forest Service 1959)

Large forest fires offer opportunity to obtain fundamental information on fire behavior. On an ongoing fire, we can study rate of spread, characteristics of the flame front, and action of the convection column in relation to fuel, topography, and weather. However, the use of large fires as a source of basic data requires development of equipment and techniques for measuring these key variables. During 1958, we started developing plans for organizing a mobile fire research team that could move rapidly with necessary equipment to the scene of a fire.

The Coal Creek Fire in Glacier National Park (August 1958) gave an excellent opportunity to test this method of gathering research infor-

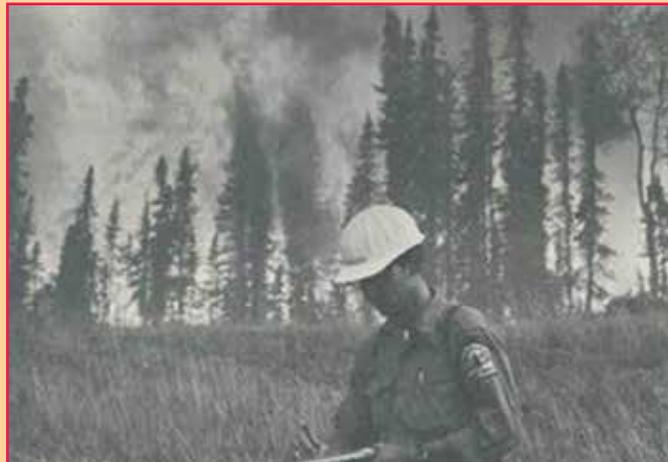
mation. Prompt relay of information about this fire to the forest fire research staff at Missoula enabled a six-man team to be dispatched to the scene fast enough for measurement and observation of fire behavior during the second—and most important—period of the major fire activity. Observations and measurements were continued through the fourth day of fire activity. This research team included two research foresters, two research meteorologists, a forestry aid, and an airplane pilot. Their equipment included a Cessna 180 aircraft instrumented for temperature, humidity, and pressure measurements; two portable fire-weather stations; four belt weather kits; four time-lapse motion picture cameras; three FM portable radios; and other miscellaneous gear. This operation showed that such a team equipped for both aerial and ground measurement of fire behavior factors can gather important basic data needed in our research program.

1969 Fire Season, Alaska (from USDA Forest Service 1970)

Over 4 million acres [1.6 million ha] of forest and rangeland burned in interior Alaska during 1969, contributing to one of the worst fire seasons on record. Smoke from the fires, some of which were larger than 500,000 acres [200,000 ha], reached as far south as Washington and Montana, and the widespread smoke pall over Alaska was so great that it was seen and recorded by weather satellites. During the period, we made rate-of-spread measurements on several fires in cooperation with the Office of Civil Defense and the Bureau of Land Management. Rates of spread on the Swanson River Fire exceeded 1 mile per hour. This study of free-burning, field-size fires provides a basis for testing predictive fire behavior models for use by firefighters in planning fire control strategies.



Portable fire weather station developed by the Forest Service's Intermountain Forest and Range Experiment Station of Forest Fire Research in use at the scene of the Coal Creek Fire.



A Forest Service fire researcher with the Pacific Northwest Forest and Range Experiment Station collecting information on rate of spread and supplementary data on the Swanson River Fire for fire behavior analysis purposes.

HUNTINGTON FIRE DEPARTMENT GETS A NEEDED TRUCK

Gary Lawrence

Located in the rural area of western Arkansas on U.S. Highway 71, our community began as a coal mining town and, as most rural towns in Arkansas, we still have some of the buildings that were built during the mining days. Our fire department works out of one main station and one mutual aid station to cover 31 square miles (80 km²) with a population of approximately 2,000 residents. With 18 fire department members, we respond to 100 to 200 calls per year. With this use, our fire department needed a new truck.

The Arkansas Forestry Commission obtained a 1985 M-936-A2 5-ton military wrecker truck with 2,985 miles (4,800 km) from the U.S. Department of Defense Firefighter Property program and offered it to us. We went right to work on the conversion to a fire truck: removing the wrecker bed and painting the truck, including the frame and interior of the cab. We installed a new flatbed along with a new APR Plastic Fabricating's 2,000-gallon (7,600 l) poly tank. The Newton air-operated swivel dump chute that we installed at the rear of the tank can be operated from either inside the cab or at the back of the truck. We also installed a new CET Fire Pump MFG's gasoline-powered pump purchased from Arkansas Forestry Commission, with controls mounted inside the cab. We installed an Elkhart Brass Sidewinder remote-controlled 125-gallons/minute (473 l/min) nozzle on the front

Gary Lawrence is the fire chief of the Huntington, AR, Fire Department.



bumper, it also has controls also inside the cab. On the right side of the tank is a 8-foot (2.5-m) wide by 16-foot (4.8-m) long, double-fold dump tank made by Husky Portable Containment. The truck has a Red Dot roof-mounted air conditioner and tinted windows.

Now named "Beast," the truck is a multipurpose truck that can be used as a tanker; as a brush truck, since it is all-wheel-drive with a front nozzle; and as a pumper, with the pump supplying two fire attack water lines. All controls are mounted inside the cab for ease of operation and safety: when arriving on scene, the driver can begin spraying water without stopping the truck or leaving the cab, avoiding the heat and smoke of a fire.

The "Beast" goes on most of the calls because it can fight brush

or grass fires, as well as structure fires. For example, the truck worked with the Arkansas Forestry Commission on a brush fire on the side of a rocky hill where firefighters needed help controlling the established fire line until a bulldozer could get to the location. Although no other trucks could get in, the "Beast" made it in and kept the brush fire under control until the bulldozer could put a firebreak around it. On a recent structure fire, the "Beast" was first to arrive on scene and put water on the fire within seconds, keeping the fire from spreading while the other units arrived and set up operations.

This piece of equipment has enabled the Huntington Fire Department to effectively attack many types of fires. It has become a symbol of our readiness and a tremendous asset to our community. ■

In Fire Management Today 73(3), the author of the article “Firewise: Empowering Wildland-Urban Interface Residents To Take Responsibility for Their Wildfire Risk” was incorrectly identified. The correct author is Michele Steinberg.

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