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 ($3.0^2 = 9$).

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

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 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

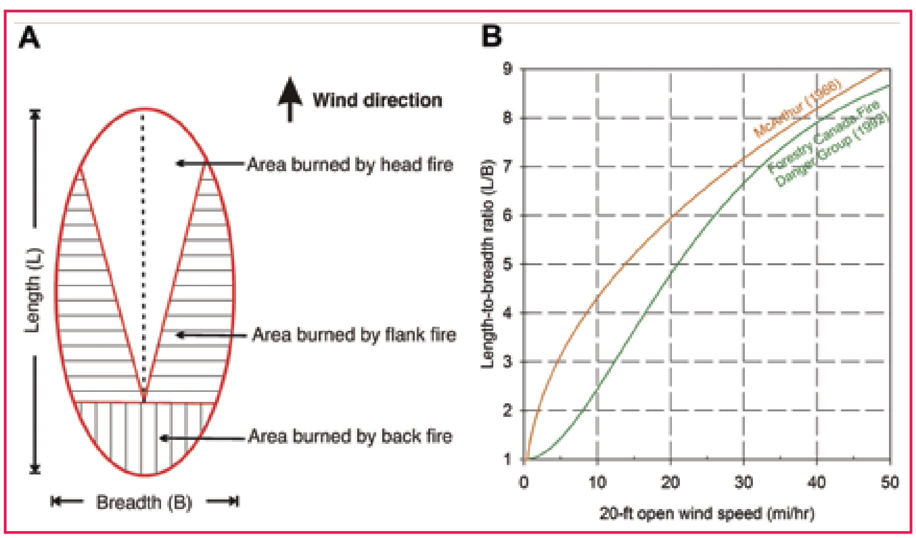

Figure 1. —*(A) Schematic diagram of a simple elliptical fire growth model (after Van Wagner 1969) with the point of ignition represented by the junction of the four area growth zones and (B) the length-to-breadth ratio of elliptical shaped surface and crown fires in conifer forests on level to gently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

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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 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.

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 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.

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

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	2693,28	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).

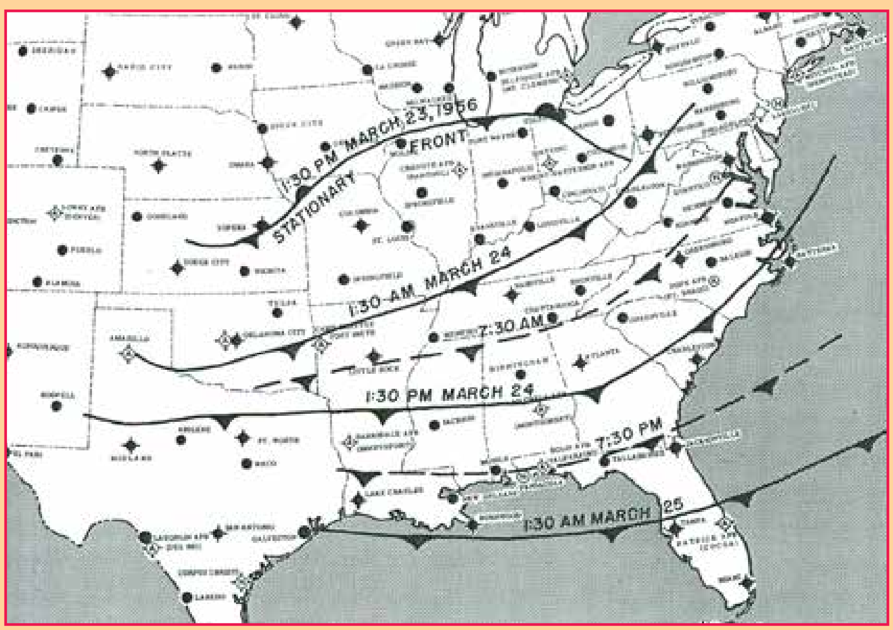
The rate of perimeter growth is the speed at which a fire increases its perimeter, expressed in terms of distance per unit of time (for example: in miles per hour). In contrast to the rate of area growth, the rate of perimeter growth remains constant with time provided the head fire rate of spread remains 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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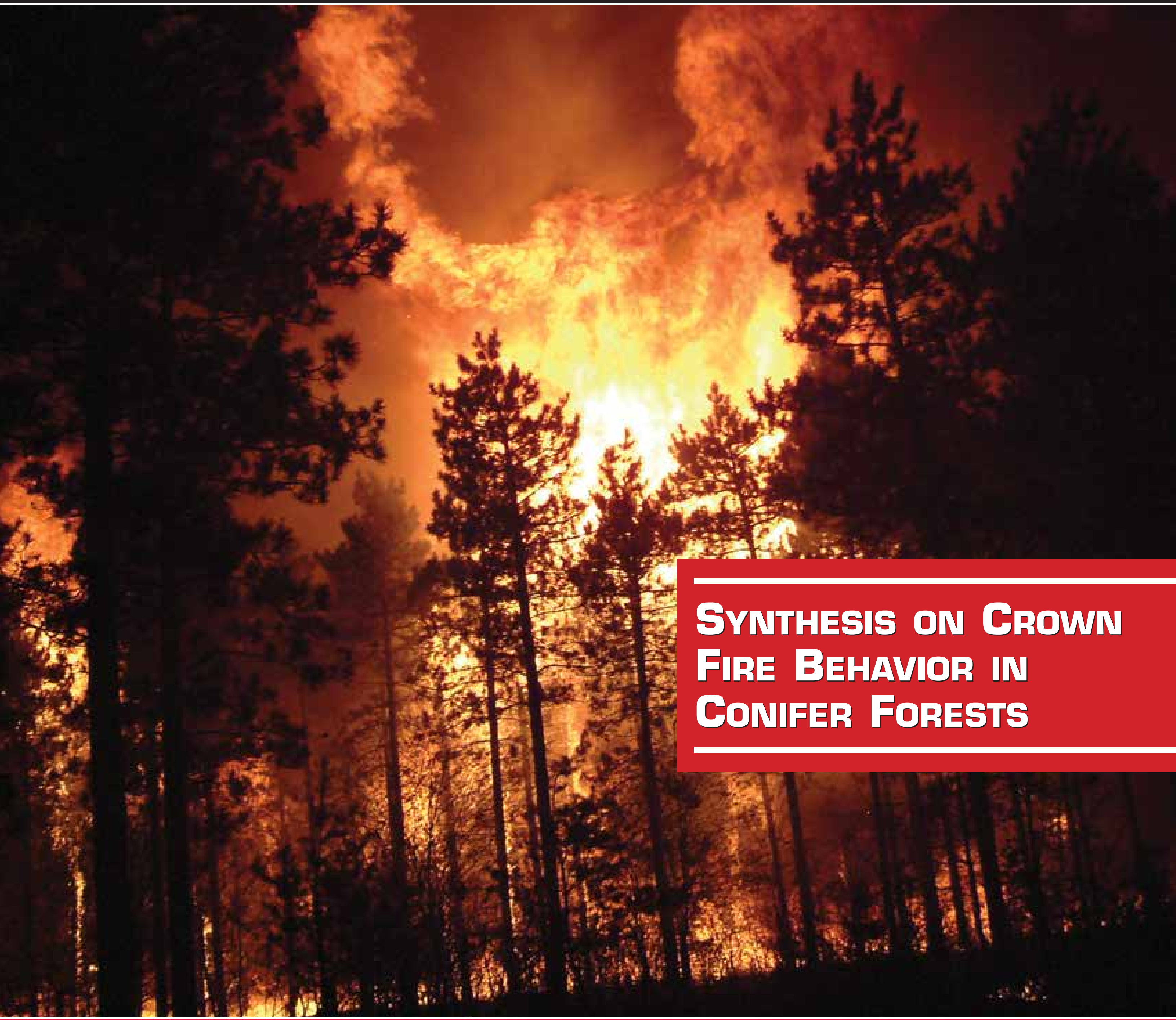

Synthesis on Crown Fire Behavior in Conifer Forests

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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.

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