The impact of fire suppression, vegetation, and weather on the area burned by lightning-caused forest fires in Ontario

David L. Martell and Hua Sun

Abstract: We describe the development of a statistical model of spatial variation in the area burned by lightning-caused forest fires across the province of Ontario. We partitioned Ontario's fire region into 35 compartments, each of which is relatively homogeneous with respect to its vegetation, weather, and the level of fire protection it receives. We used linear regression and spatial autoregressive models to relate the average annual area burned in a compartment to its vegetation, weather, and level of protection attributes. We also examined the relationship between burned area and the level of protection in two areas that are relatively homogeneous with respect to vegetation and weather. We found a statistically significant relationship between the average annual fraction of the area of a compartment burned by lightning-caused forest fires and its vegetation, weather, and the level of fire suppression effort it receives.

Résumé : Nous décrivons le développement d'un modèle statistique de la variation spatiale de la superficie détruite par les incendies de forêt causés par la foudre dans la province d'Ontario. Nous avons divisé la région des feux de l'Ontario en 35 compartiments. Chacun de ces compartiments est relativement homogène quant à la végétation, aux conditions météorologiques et au niveau de protection contre les incendies. Nous avons utilisé des modèles de régression linéaire et la modélisation spatiale autorégressive pour relier la superficie annuelle moyenne détruite par le feu dans un compartiment aux caractéristiques de sa végétation, de ses conditions météorologiques et de son niveau de protection. Nous avons aussi examiné la relation entre les superficies détruites par le feu et le niveau de protection dans deux zones avec où la végétation et les conditions météorologiques sont relativement homogènes. Nous avons trouvé qu'il y a une relation statistiquement significative entre la fraction annuelle moyenne de la superficie d'un compartiment qui est détruite par des incendies de forêt causés par la foudre et sa végétation, ses conditions météorologiques et le niveau d'effort consenti pour y supprimer les feux.

[Traduit par la Rédaction]

Introduction

Most Canadian forest fire management agencies were established late in the 19th century or early in the 20th century in response to threats to public safety, property, and forest resources.[3] Their fire exclusion policies called for prevention, detection, aggressive initial attack, and large fire suppression to limit the area burned by wildfires. Modern fire suppression systems, information technology, and continentwide fire suppression resource-sharing agreements now make it possible for forest fire management agencies to mobilize and deploy very powerful but costly fire suppression forces much more quickly and easily than they could in the past. Growing recognition that fire is a natural component of many forest ecosystems, fuel buildups in some forested ecosystems, pressure to reduce government expenditures, and demands for increased protection of forest resources and communities are encouraging many agencies to revise their traditional fire exclusion policies in favour of aggressive suppression of fire in high-value areas, as they gradually move towards leaving and putting more fire on the landscape to support natural fire-dependant ecosystem processes where there is little or no perceived threat to public safety, property, or forest resources (see, for example, Pyne 2004).

North American forest fire management agencies have traditionally provided levels of fire protection that vary significantly across the area under their jurisdiction. The province of Ontario, for example, was until recently, partitioned into three large fire management zones. The level of protection varied by zone, but was reasonably homogeneous within each zone.[4] Because of the changes described above, there is a growing need for fire management that delivers a level of protection that varies across the landscape in response to spatial variation in human needs and natural eco-

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D.L. Martell[1] and H. Sun.[2] Faculty of Forestry, University of Toronto, 33 Willcocks Street, Toronto, ON M5S 3B3, Canada.

[1]Corresponding author (e-mail: martell@smokey.forestry.utoronto.ca).
[2]Present address: Wildfire Resource Information Section, Alberta Sustainable Resources Development, 9th Floor, 9920-108 Street, Edmonton, AB T5K 2M4, Canada.

[3]See, for example, Lambert (1967), who traces the development of fire management in Ontario beginning in 1878, and Blanchet (2003), who documents the fire management history of Quebec beginning in 1870.
[4]On 7 May 2004, the Ontario Ministry of Natural Resources (OMNR) announced the introduction of a new fire management strategy under which the fire region was partitioned into six new fire management zones that vary with respect to land use, resource management, and fire management objectives. The new strategy is described in Ontario Ministry of Natural Resources (2004).

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system processes. The development and implementation of such spatially explicit fire management policies is predicated on an ability to predict the impact of and then vary levels of fire protection across vast forest landscapes. In this paper we describe the development of a methodology that relates spatial variation in the area burned by lightning-caused forest fires to the level of fire protection, vegetation, and weather across Ontario. We also address the debate about the extent to which "fire suppression"[5] has reduced area burned in Ontario.

We begin with a brief overview of previous attempts to relate area burned in Ontario to fire suppression and other factors and touch on some of the debate that ensued. We then describe our study area, the fire region of the province of Ontario, develop a conceptual stochastic process model that relates annual area burned in Ontario to vegetation, weather, and fire suppression effort, and describe how we partitioned our study area into 35 compartments that are relatively homogeneous with respect to those three factors. We describe how we developed surrogate measures of fire control difficulty (based on vegetation and weather) and level of fire protection, a linear regression model that relates annual area burned to those two measures, and the results we obtained when we applied that model to the province of Ontario. We conclude with a discussion of our results and future research.

The impact of fire suppression on area burned — An historical perspective

Miyanishi and Johnson (2001) addressed the issue of fire suppression effectiveness in the boreal forest, and stated "Often it is assumed that fire suppression has been effective... Unfortunately, there is little good data in support of this assumption." This stands in stark contrast to the opinions of many North American forest fire managers that have long believed that fire suppression reduces area burned, but who, with very few exceptions, documented their studies and findings in internal government reports. Sparhawk (1925) developed the theoretical foundation for the least cost plus damage (LCD) model for determining an optimal fire management budget that balances fire management expenditures and fire losses on the assumption that burned area is a decreasing function of fire management effort. He used climate data to partition the western half of the United States (excluding Alaska and Hawaii) into 21 subregions and then classified the forest cover type in each subregion. He then related the burned area in each cover type within each subregion to the subregion's initial attack response time. His approach is, in some respects, an early version of the methodology we have developed and applied to Ontario.

Quimby Hess, the Supervisor of Fire Control in the Ontario Department of Lands and Forests (ODLF), related burned area in Ontario to fire protection expenditures. He described his findings in an unpublished 1958 internal memorandum to A.P. Leslie, Chief of the Research Branch of the ODLF. The ODLF subsequently contracted the firm Stevenson Kellog, which, like Hess, developed graphs that related the average fraction of the area burned in each of 22 forest districts in Ontario (that covered a total of 113×10^6 acre; 1 acre = 0.4047 ha) to the annual presuppression budget. Our paper is in many respects an extension of their work, although we use initial attack response time (rather than the presuppression budget) as a measure of suppression effort, which we augment with an integrated measure of weather and vegetation. In 1974, Glenn Doan of the Forest Protection Branch of the ODLF developed a provincial protection possibility curve that related average fire size to presuppression expenditures. His work was used to document a fire protection proposal to Ontario's Management Board of Cabinet, which was subsequently updated in 1981 and then used to set regional burned area targets that were incorporated into regional fire management strategies.

Ward and Tithecott (1993) examined Ontario's historical fire data and the age-class structure of much of the intensive protection zone in the fire region in Ontario and concluded that "human activity, both the actions of people in causing forest fires and their actions in managing and suppressing fires, has significantly altered the structure of Ontario's forests." Miyanishi and Johnson (2001) questioned the quality of their data, the way it was analyzed, and their conclusions. They suggested that the perceived change in fire regimes in the boreal forest region of Ontario is not "necessarily attributable to fire suppression" since "changes in fire frequency in the boreal forest have been also attributed to climate change and anthropogenic forest fragmentation." Ward et al. (2001) responded with an expanded version of their analysis that better substantiated their earlier findings. Bridge et al. (2005) then responded with what they describe as a "critical evaluation of fire suppression effects in the boreal forest on Ontario" in which they questioned the validity of Ward et al.'s (2001) findings and concluded "to date, there is insufficient empirical evidence that fire suppression has significantly changed the fire cycle in the boreal forest of Ontario."

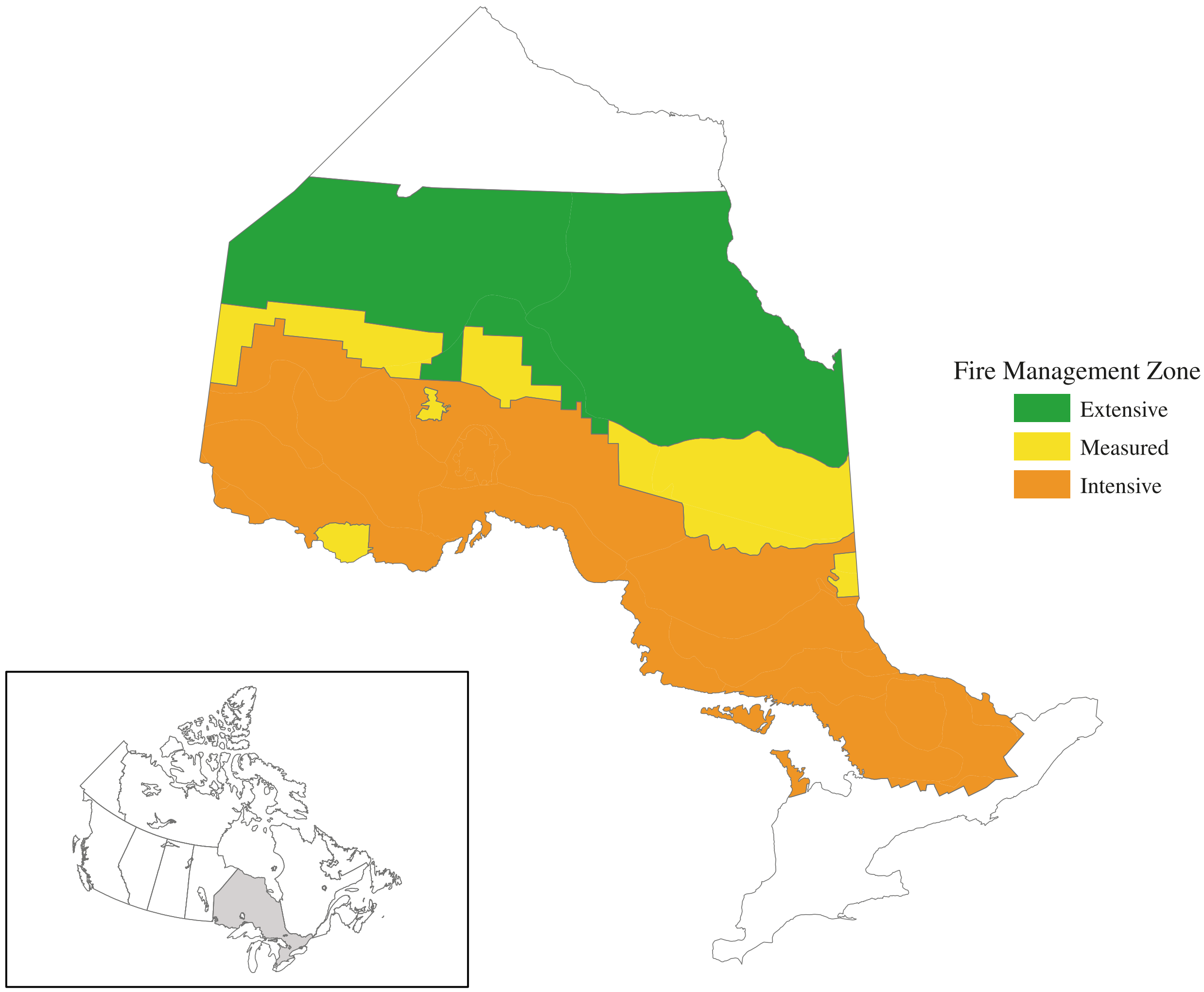
Martell (1994) reported that the average annual burn rate (fraction of the protected area burned) in Ontario over the 13 year period from 1976 to 1988 increases as one moves from the intensive protection zone (0.00181), through the measured protection zone (0.00248) to the extensive protection zone (0.00438). Miyanshi et al. (2002) and Bridge et al. (2005) questioned the value of that evidence because forest type, climate, land use, and other potentially confounding factors had been ignored and that the 13 year sample size was, in their judgement, too small. In this paper we use a larger (19 year) sample of fire data and explore the impact of many of those factors on burned area.

Study area

Our study area is the 776 770 km^2 fire region of the

[5] We use the term fire suppression to refer to the broad range of activities that forest fire management agencies use to minimize burned area and damage. Such activities may include fire prevention and related law enforcement measures, detection, initial attack by fire fighters that travel to fires by truck or by air and are often supported by airtankers, and the mobilization of incident management teams charged with the responsibility for containing the growth of large fires that escape initial attack. Fire suppression can also include fuel treatment measures designed to slow fire growth and reduce fire intensity, and the development and implementation of building codes designed to reduce the likelihood that houses and other structures will be damaged by fires that burn through wildland – urban interface (WUI) areas.

Fig. 1. Ontario's forest fire management zones.



1 076 395 km² province of Ontario in central Canada (see Fig. 1). The fire region is formally designated by the *Forest Fires Prevention Act* (Revised statutes of Ontario 1990), provincial government legislation that pertains to forest fires and assigns the responsibility for fire management to the Aviation and Forest Fire Management Branch (AFFMB) of the OMNR.

The fire region was partitioned into intensive, measured, and extensive fire management zones up until 7 May 2004. The intensive protection zone covered 361 206 km² where fire poses a significant threat to public safety, property, and other values. All fires in the intensive zone were to be fought aggressively until they were extinguished. The measured protection zone was a 112 193 km² area where fire had less potential to damage isolated tourist camps, industrial facilities, and other values. All measured protection zone fires were to be attacked, but those that could not be controlled by the initial attack force were subjected to escaped fire situation analyses that might have prescribed limited suppression action until they were extinguished. Fires that occurred in the 303 371 km² extensive protection zone were not attacked unless they posed significant threats to public safety or property. The level of protection was greatest in the intensive zone, least in the extensive zone, and the measured zone was a transition zone that received an intermediate level of protection.

The percentage or proportion of area burned by fire exhibits very large spatial and temporal variation across Ontario. Martell (1994) reported 1976–1988 average annual burn rates that varied from 0.004% of the 6792 km² intensive protection zone in the Kapuskasing district in northeastern Ontario to 1.5% in the 13 916 km² intensive protection zone in the Kenora district in northwestern Ontario. The annual burned area within the intensive protection zone of the Kenora district during that period ranged from 12 ha in 1978 to 127 913 ha in 1980.

When investigating the potential impact of fire suppression and other factors on area burned one must be cognizant of temporal and spatial changes in climate, vegetation, demographics, land use patterns, fire suppression technology, fire suppression policies, and budget levels that cannot always be rigorously documented, yet may confound the results. One can study fire activity in a designated area over time (longitudinally), as Cumming (2005) did, or one can study fire activity during a designated time period across space (cross sectional with respect to time). Longitudinal studies of fire management systems are fraught with difficulties in identifying and quantifying changes in technology and fire management policies. We therefore opted for a cross-sectional analysis of fire activity in Ontario. Our implicit assumption is that we can identify a time period during which fuel, climate, technology, budgets, and policies remained relatively stable, but where fuel, weather, and level of fire protection varied over space. We restricted our attention to a 19 year period during which we believe it is reasonable to assume Ontario's fire management program remained relatively stable. We expanded our study to cover almost all of Ontario's roughly 777 000 km^2 fire region to capture the variation in fuel, weather, and level of protection we require to investigate the impact of those factors on fire activity.

Forest fire management was formally introduced in the province of Ontario with the passage of the 1878 *Fire Act*, which called for the formation of two fire districts and the restricted use of fire during hazardous periods, but it did not begin in earnest until 1917 with the passage of the *Forest Fires Protection Act* and the formation of the Ontario Forestry Branch, a predecessor of the OMNR (Lambert 1967). The government of Ontario gradually expanded its influence across the province and its fire management program grew in strength over the years, but remained relatively stable from the early 1970s until the early 1990s. During the years 1976–1994, the OMNR's base budget for fire management (expressed in terms of 1986 Canadian dollars) ranged from \$25 million to \$35 million and averaged \$30 million. The 1976 and 1994 base budgets were both \$29.3 million. We restricted our analysis to the period 1976 through 1994, years during which we believe there were few significant changes in climate, vegetation, land use patterns, or the OMNR's fire management program.[6]

Roughly 38% of the forest fires that occur in Ontario are caused by lightning. The remaining 62% are caused by people, yet lightning-caused fires produce 75% of the area burned (Wotton et al. 2003). People-caused fire occurrence processes are heavily influenced by land use patterns, human behaviour, and fire prevention measures in ways that are often difficult to document and quantify. We therefore limited our analysis to lightning-caused fires and reserved people-caused fires for future study. We partitioned the province into 35 compartments that appear to be reasonably homogeneous with respect to fuel, weather, topography, land use patterns, and level of fire protection, and we carried out a cross-sectional analysis of the impact of fuel, weather, and level of fire protection within each compartment on the average annual area burned by lightning-caused fires. More details on the formation of these compartments follow in the Methods section.

A conceptual model

The ignition, spread, and eventual extinction of forest fires is governed by many factors including fuel, weather, topography, and suppression efforts. Assume a fire management agency has allocated resources to prevent, detect, and suppress fires in a designated area that we will henceforth refer to as the protected area. Furthermore, assume that this protected area has been partitioned into a large number of homogeneous compartments.

Assume frontal and air mass thunderstorms pass over the compartments at rates that depend upon synoptic and mesoscale weather patterns and produce precipitation and cloud-to-ground lightning strokes, and that a very small proportion of lightning strikes will ignite fires depending upon the properties of the strikes and the composition and moisture content of the forest vegetation. Lightning fire ignition probability is influenced by the properties of the forest vegetation including its moisture content (see, for example, Wotton and Martell 2005). If the surface fuels are sufficiently dry and wind speeds are sufficient, the fire will begin to spread as an active surface or crown fire almost immediately. If the surface fuel is damp but the deeper organic layers are dry, the fire may move into the deep organic layer where it will smoulder as a "holdover" fire until it expires because of a lack of flammable fuel or until the surface fuel dries to a point where it can sustain active surface fire growth (see, for example, Wotton and Martell 2005).

Holdover fires that survive until the surface vegetation becomes dry enough to support sustained combustion will emerge and emit readily visible smoke as they spread through the forest. Those that are eventually detected and reported to a forest fire management agency are classed as "arrivals". Fire arrivals that require suppression action are placed in the initial attack queue where they wait until an initial attack crew becomes available. An initial attack crew is then dispatched and usually attempts to contain the fire at a small size. Fires that cannot be contained are classed as "escaped" fires and have the potential to burn over very large areas.

Suppression tactics will be governed by many factors including the terrain and fuel in which the fire is burning, fire behaviour, fire fighter safety, and values at risk. The keys to the successful containment of large escaped fires are to establish control lines on low intensity portions of the active fire perimeter (e.g., when and where the fire is backing into the wind, burning in the direction from which the wind is blowing), burn out flammable vegetation and create barriers in advance of the fire, and deploy suppression forces near the fire so they can strike hard as soon as favourable weather conditions materialize. The objective is to contain the fire during any lull in intensity that accompanies relatively cool, moist, calm weather and extinguish it so it cannot continue to burn freely during any subsequent dry and windy periods that may materialize before cold, wet fall and winter weather conditions extinguish the fire. Fire management agencies thus have the potential to reduce burned area by finding and containing fires while they are small by means of initial attack efforts and by reducing the time that large escaped fires burn freely.

A mathematical model of burned area

Let us assume the protected area can be partitioned into a

[6] During the 1980s, the OMNR replaced Canso, Otter, and Turbo Beaver aircraft, which were used for water bombing, with CL-215 airtankers. During the 1990s, the CL-215s were replaced with CL-415s. Although these technological innovations are believed to have contributed to enhanced productivity, the OMNR continued to rely on fire fighters supported by airtankers, and the extent to which the new airtankers reduced the cost of fire suppression and (or) reduced area burned has not been formally documented.

number of compartments, each of which is relatively homogeneous with respect to forest vegetation, weather, and level of protection. Let L denote the level of protection, S the lightning regime, V the forest vegetation, and W the weather or climate of a particular compartment. Lightning fires are ignited by cloud-to-ground lightning strikes generated by thunderstorm cells. Cunningham and Martell (1973) found it was reasonable to model daily people-caused fire occurrence as a Poisson process. It is also reasonable to model lightning fire occurrence as a Poisson process (see, for example, Wotton and Martell 2005). Although lightning fire arrival rates vary over both time (e.g., by day) and space (across the province), we are interested in modelling the fire arrival processes on an annual basis and will assume the lightning fire occurrence process in a compartment is Poisson with an arrival rate of $\lambda(S,V,W)$ lightning fires per square kilometre per year.

Let $P_{esc}(V, W, L)$ denote the probability that a fire which occurs in a compartment will escape initial attack and assume it depends upon the forest vegetation, the weather, and the level of protection in the compartment. Let A denote the size of the compartment (measured in the same units as area burned, in our case, square kilometres). Fires that are controlled by the initial attack force are assumed to burn no significant area, but escaped fires have the potential to burn a large area. We ignore the small area burned by fires that are controlled by the initial attack force and assume the area burned by an escaped fire has some probability distribution with a mean $\mu(V,W,L)$ that depends on V, W, and L. The probability distribution of the number of escaped fires during the half open time interval $(0,t]$ will be Poisson (owing to random thinning of the Poisson fire arrival process, Daley and Vere-Jones 2003, p. 34) with a mean of

$$\lambda(S, V, W) \times A \times P_{esc}(V, W, L) \times t$$

The area burned will have a compound Poisson distribution with a mean of (see Ross 1970)

$$\lambda(S, V, W) \times A \times P_{esc}(V, W, L) \times t \times \mu(V, W, L)$$

The expected fraction of the area burned during time t will be

$$[1] \qquad f = \lambda(S, V, W) P_{esc}(V, W, L) \mu(V, W, L) t$$

Note that although f can, in theory, exceed 1, the sizes of our compartments are such that there is little or no likelihood of that happening.

The fire arrival rate, $\lambda(S,V,W)$, no doubt varies across Ontario but has not yet been be documented, so for now we will assume it is constant across all compartments. The average annual fraction of the burned area within a compartment should therefore be proportional to the product of two functions, $P_{esc}(V,W,L)$ and $\mu(V,W,L)$, both of which should vary with fuel, weather, and the level of protection in the compartment.

Given these assumptions, our next task was to partition Ontario's fire region into a set of compartments that are reasonably homogeneous with respect to fuel, weather, and level of protection, which can serve as our basic spatial unit of analysis, estimate the average annual burn fraction of each compartment, and then identify covariates that can serve as surrogate measures of the fuel, weather, and level of protection attributes of each compartment.

Methods

Spatial analysis compartments

We began with a digital map of the forest sections of Rowe's (1972) forest region ecological classification system, a set of compartments that are relatively homogenous with respect to fuel and weather. We then overlaid the OMNR's fire management zone coverage (Fig. 1) atop the forest section coverage. This intersection of the forest section and fire management zone coverages produced a set of 76 polygons that are relatively homogeneous with respect to fuel, weather, and level of protection.

Some of those polygons were very small and some were very long narrow "slivers" produced by the intersection of large polygons with boundaries that were close to, but not coincident with, each other. We used the ARC/INFO "elimination" command (see Chou 1997) to dissolve 20 polygons that were <100 km^2 in size into their largest adjacent polygon, and we subjectively joined slivers and other small polygons that had irregular perimeters or very small areas to adjacent polygons. Our final map contains 35 fire management compartments. Given this spatial coverage of the fire region, we then estimated the average annual burn fraction, weather, fuel, fire behaviour potential, and level of protection attributes of each compartment (Table 1).

Estimating the average annual burn fraction

The OMNR prepares detailed fire reports for all forest fires that are known to have occurred in the fire region. Each fire report describes many fire attributes including the point where it is known or was estimated to have been ignited, the date it is known or was estimated to have started, the time suppression action began, and the fire's final size. The AFFMB provided us with computer readable fire reports for the years 1976–1994. We assumed all the area burned by a fire fell within the compartment in which it started, and we used the reported final fire sizes to compute the average annual burn fraction of each compartment. Each compartment in the map in Fig. 2 is numbered and colour coded with respect to the average annual burn fraction over the 19 year period of 1976–1994. The average annual burn fractions are shown in Table 1 and range from 6.2×10^{-7} to 1.0×10^{-2} with an average of 1.0×10^{-3} and a stnadard deviation of 2.2×10^{-3}.

Assessing the weather, fuel, and fire behaviour potential attributes of a compartment

Having partitioned the fire region into a set of compartments that are reasonably homogeneous with respect to fuel, weather, and level of protection, we needed a set of weather, fuel, and fire behaviour potential parameters that could be used to model the potential of fires to escape initial attack and spread in each of those compartments.

Weather

Weather has a very significant impact on fire activity, but raw weather data alone (e.g., temperature or precipitation) pro-

Table 1. Summary of forest fire activity in 35 fire management compartments across the province of Ontario, 1976–1994.

Forest section	Forest section code	Fire management zone	Fire management compartment No.	Area (km^2)	ADSR	FCDI	IAI (h)	LOP (h)	BF (fraction)
Huron–Ontario	L.1	I	166	1 866	1.29	14.08	0.69	0.33	0.000 001 04
Northern Coniferous	B.22a	E	6	123 119	1.13	15.98	15.38	1.87	0.009 998 24
Northern Coniferous	B.22a	M	12	26 338	1.29	17.41	6.69	1.00	0.005 935 16
Northern Coniferous	B.22a	I	13	17 375	1.17	16.43	3.18	0.82	0.002 106 51
Central Plateau	B.8	M	15	13 408	0.87	15.37	9.43	1.40	0.000 608 05
Central Plateau	B.8	E	16	3 503	0.70	14.39	10.38	1.17	0.000 070 01
Central Plateau	B.8	M	19	1 554	0.70	14.39	1.60	0.58	0.000 014 22
Central Plateau	B.8	M	25	1 602	0.67	13.16	20.71	1.42	0.001 918 57
Huron–Ontario	L.1	I	156	2 888	1.29	14.08	4.56	1.04	0.000 001 46
Central Plateau	B.8	E	11	14 491	0.90	15.66	37.70	1.48	0.005 375 83
Lower English River	B.14	I	40	14 052	0.92	11.54	3.44	0.78	0.003 511 15
Upper English River	B.11	I	21	40 795	0.90	11.30	2.49	0.77	0.000 678 79
Quetico	L.11	I	29	39 446	1.03	9.28	2.72	0.68	0.001 868 04
Central Plateau	B.8	M	30	7 264	1.30	17.81	2.95	0.85	0.000 259 81
Rainy River	L.12	I	58	3 211	0.80	3.99	1.32	0.82	0.000 002 00
Quetico	L.11	M	70	4 813	0.78	8.25	3.50	0.88	0.000 014 06
Algoma	L.10	I	92	12 801	0.69	2.32	6.13	1.17	0.000 016 63
Middle Ottawa	L.4c	I	130	13 785	1.42	4.05	1.38	0.42	0.000 020 17
Algonquin–Pontiac	L.4b	I	132	10 197	0.95	3.24	2.56	0.80	0.000 004 38
Georgian Bay	L.4d	I	133	21 696	1.07	3.73	1.48	0.42	0.000 016 40
Upper St Lawrence	L.2	I	137	2 718	1.46	15.54	0.52	0.33	0.000 006 16
Huron–Ontario	L.1	I	176	2 720	1.24	14.08	0.42	0.25	0.000 009 31
Northern Clay	B.4	M	39	44 331	1.09	5.80	2.48	0.58	0.000 023 61
Northern Clay	B.4	M	82	9 847	1.12	6.05	1.46	0.64	0.000 002 15
Missinaibi–Cabonga	B.7	M	87	1 259	0.86	8.27	0.85	0.46	0.000 002 09
Algonquin–Pontiac	L.4b	I	120	3 196	0.63	2.73	1.55	0.69	0.000 118 20
Sudbury – North Bay	L.4e	I	115	14 786	1.09	4.46	1.64	0.67	0.000 020 54
Missinaibi–Cabonga	B.7	I	76	43 585	1.16	9.86	2.81	0.83	0.000 121 24
Haileybury Clay	L.8	M	90	1 777	0.86	7.15	1.11	0.68	0.000 000 62
Haileybury Clay	L.8	I	95	886	1.14	8.09	1.15	0.50	0.000 026 73
Timagami	L.9	I	100	26 194	0.98	8.46	3.77	1.08	0.000 384 99
Central Plateau	B.8	I	62	60 102	0.92	15.69	2.63	0.78	0.000 137 25
Nipigon	B.10	I	34	4 311	0.87	15.72	5.52	0.80	0.000 700 98
Superior	B.9	I	75	24 596	0.86	8.67	3.53	0.83	0.000 130 82
Hudson Bay Lowlands	B.5	E	9	162 258	1.03	0.00	9.94	2.17	0.000 638 70

Note: BF, lightning fire burn fraction; LOP, median initial attack time; FCDI, fire control difficulty index; IAI, average initial attack interval; and ADSR, average daily fire severity rating.

Fig. 2. Average annual burn fractions across Ontario, 1976–1994.

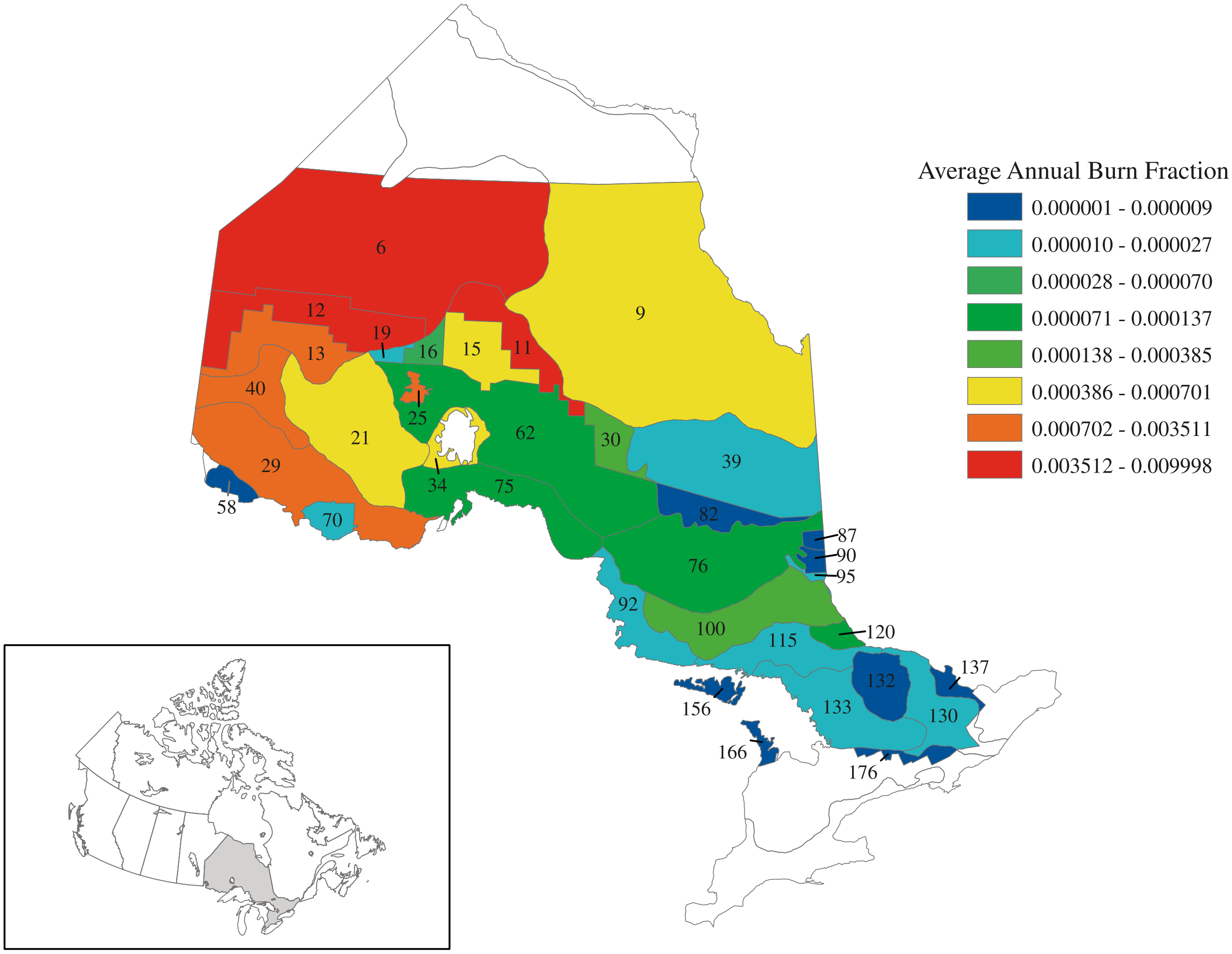


Table 2. Statistical summary of the fire management compartment characteristics.

Variable	Min.	Max.	Mean	SD	Coefficient of variation
Avg, annual burn fraction	0.000 001	0.010 00	0.000 99	0.002 14	2.15
Avg. response time (h)	0.42	37.70	5.08	7.16	1.41
Median response time (h)	0.25	2.17	0.86	0.42	0.49
Avg. fire control difficulty index	0	17.81	10.20	5.16	0.51
Avg. daily severity rating	0.63	1.46	1.01	0.22	0.22

vides little insight into potential fire activity of a compartment. For example, given two compartments that are similar in all respects other than their temperature and precipitation regimes, hot and dry compartments tend to burn more readily than hot and moist compartments. Canadian forest fire management agencies use the Canadian Forest Fire Danger Rating System (CFFDRS) to structure their use of weather data for predicting fire occurrence and behaviour and other fire management activities. The codes and indices of the CFFDRS (Stocks et al. 1989) are based on daily temperature, relative humidity, wind speed, and precipitation observations and are designed to be representative of the moisture content of selected components of the forest vegetation or fuel complex (e.g., the litter or deep duff layer) and potential fire behaviour.

The OMNR maintains a large network of weather stations where temperature, relative humidity, wind velocity, and 24 h precipitation are recorded at noon local standard time each day throughout the fire season (1 April – 31 October). The OMNR's 1976–1992 daily weather observations and fire danger rating indices were used to derive fire climate measures for each compartment.[7] The fire weather database contained observations recorded at 303 fire weather stations, some of which were closed or relocated short distances during the 1976–1992 period. With one exception (described in the following) we limited our analysis to the 75 weather stations that operated continuously for at least 10 fire seasons during 1976–1992. We assigned each compartment that contained one or more of those weather stations all the stations

[7] The 1993–1994 weather data was not available to us when we computed our FCDIs.

they contained, and we assigned each compartment that did not contain a suitable weather station the weather station that was closest to its perimeter. Compartment 40 is in the northwestern portion of the province and its closest weather station was 18 km from its perimeter. It contained one weather station that operated for 9 years and was then closed and replaced by another weather station a very short distance away that ran for 8 years. We used those two weather stations to provide a single 17 year weather record for compartment 40.

We computed the seven CFFDRS fire danger rating indices (fine fuel moisture code, FFMC; duff moisture code, DMC; drought code, DC; initial spread index, ISI; buildup index, BUI; fire weather index, FWI; and daily severity rating index, DSR) based on the weather observed at each fire weather station each day. We then averaged those values over all the fire weather stations in a compartment to obtain the averaged daily indices for each compartment for each day. Those daily compartment averages were then averaged (over all years) to produce an estimate of each compartment's average fire danger rating indices.

The DSR is a nonlinear function of the FWI that was developed in response to the fact that most fire activity (e.g., area burned) is a nonlinear function of some of the components of the CFFDRS including the FWI. Flannigan and Van Wagner (1991) cite Van Wagner (1970) and state, "The daily severity rating was designed to be a better measure of the work needed to suppress a fire than the FWI and is recommended for temporal or spatial averaging of fire danger for fire management purposes." They also present linear regression models of annual burned area as a function of the fire season severity rating (SSR, the seasonal average of the DSR) for six fire weather regions across Canada. We therefore used the average daily severity rating index (ADSR) to characterize a compartment's fire weather and climate.

Fuel and fire behaviour potential

Given our need to assess the potential impact of a compartment's fuel composition on area burned, we needed to characterize a compartment's fuel composition in terms of its fire behaviour potential. We therefore used the Canadian Forest Fire Behaviour Prediction (FBP) system to structure our use of fuel data. The FBP system is a series of mathematical models that relate fire spread rates and other fire characteristics to weather and fuel parameters (Forestry Canada Fire Danger Group 1992). The FBP system classifies forest vegetation into discrete fuel types or fuel models based on the dominant vegetation (e.g., fuel type C-3 is mature jack pine (*Pinus banksiana* Lamb.) or lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.)). Fire behaviour predictions are based on statistical models derived from observations of experimental burns of homogeneous experimental plots that ranged from roughly 0.2 to 2.0 ha in size supplemented by observations of large, well-documented wildfires.

We estimated the area of each forest compartment covered by each FBP fuel type as follows. Bickerstaff et al. (1981) used provincial forest inventory data to produce subjective estimates of several attributes of Rowe's (1972) forest sections. They reported the percentage of each of Rowe's forest sections that were productive forest land (land supporting tree growth that they judged to be merchantable for industrial purposes), improved land (land used for urban or industrial development, transportation, and farming), and all other land that they classed as wildland. We combined the productive forest land and wildland to obtain a forest land percentage for each forest section. Bickerstaff et al. (1981) reported the major tree species by volume to the nearest 10% for all of Rowe's (1972) forest sections. We used that information to estimate fuel type percentage in each of Rowe's forest sections as described in the following.

The FBP fuel type C-2 (boreal spruce) includes "moderately well-stocked black spruce stands on both upland and lowland sites; sphagnum bogs excluded". C-2 is based largely on experimental burns conducted on relatively dry sites and is therefore not representative of moist lowland spruce sites that occur in parts of Ontario, particularly the Hudson Bay Lowlands. We had to determine how much of Ontario's spruce forest cover to treat as C-2, upland spruce, and how much to treat as lowland spruce. We did this by studying Rowe's (1972) verbal descriptions of each forest section and determining subjectively if what Bickerstaff et al. (1981) described as spruce within each forest section was 0%, 25%, 50%, 75%, or 100% upland spruce.

One of the FBP fuel types (O-1) is grass. Dead and cured grass often plays a significant role in fire ignition and spread processes. Unfortunately, Bickerstaff et al. (1981) did not provide any estimates of the abundance of what fire managers would classify as a grass fuel cover type. Grass often grows in and around communities along transportation and telecommunications corridors such as railways, highways, and electric power transmission lines. Bickerstaff et al. (1981) did, however, provide estimates of the percentage of each forest section that was classified as "Improved" land, which they described as land that is "used for urban or industrial development, transportation facilities, institutional use, and farming." Therefore, we classified all such land, 20 514 km^2 or 3.3% of our study area, as grass.[8]

There is no FBP fuel type for moist lowland spruce because it is not considered to be a high-priority fuel owing its relatively low flammability under normal weather conditions and that made it difficult for us to estimate the FCDI of compartments dominated by lowland spruce. That lack of an FBP fuel type mostly affects compartment 9, which lies in Rowe's Hudson Bay Lowlands (B.5) along the southwest coasts of Hudson's Bay and James Bay. In the Results section, we describe why that made compartment 9 a very influential compartment, which we decided to exclude from our model.

We aggregated the Bickerstaff et al. (1981) estimates of volume percentages of balsam fir (*Abies balsamea* (L.) Mill.) and jack pine to produce an areal estimate of the percentage of each forest section that was C-4 (immature jack pine or lodgepole pine). Their red pine (*Pinus resinosa* Ait) and eastern white pine (*Pinus strobus* L.) estimates were aggregated to produce estimates of C-5 (red and white pine) percentages by forest section.

[8] We began with a 776 770 km^2 study area, which was reduced to 614 512 km^2 when, as described, we removed the Hudson Bay Lowlands forest section from our analysis.

Fire control difficulty index

Weather and fuel parameters alone are not sufficient to gauge the potential fire behaviour and likelihood that suppression forces could contain any fires that ignite in a compartment. A compartment that contains flammable fuel will not burn if the weather is cool and humid. On the other hand, a hot, dry compartment will not burn if it does not contain flammable fuel. Therefore, we developed and tested a new fire control difficulty index (FCDI), which is designed to serve as an integrated measure of the potential impact of both fuel and weather on area burned.

Our FCDI is an index of the potential head fire intensity[9] of fires that occur in a compartment and is based on the daily CFFDRS fire danger rating indices and the Canadian FBP fire behaviour prediction models (Forestry Canada Fire Danger Group 1992). The structure of our FCDI is motivated by the widely accepted understanding (see, for example, Hirsch et al. 1998) that the ability of an initial attack crew to control a fire is a decreasing function of its frontal fire intensity.[10] Byram (1959) developed an empirical relationship that relates the flame length of a fire burning in a homogeneous fuel type to the square root of its frontal fire intensity. Since fire fighters can observe and subjectively gauge flame length much easier than they can measure frontal fire intensity, we developed an FCDI that is a linear increasing function of the square root of fire intensity as described in the following.

Let n days denote the number of days that fire weather was observed at one or more fire weather stations in compartment m during May–September and let i denote the ith day on which fire weather is observed in compartment m. We used the FBP system and the fire weather observed at weather station j on that day to compute I_{ijkm}, the frontal intensity of a hypothetical fire that ignites and burns in fuel type k in compartment m on that day, based on the fire weather observed at weather station j. We then averaged (over all the fire weather stations in compartment m) the square root of each of the I_{ijkm} frontal fire intensities to compute FCDI_{ikm}, the intermediate fire control difficulty index associated with fuel type k in compartment m on day i. We then averaged FCDI_{ikm} over all n days to compute the intermediate index FCDI_{km} associated with fuel type k in compartment m. Let C_{km} denote the percentage of the area of compartment m that is covered with fuel type k, which ranges from 1 to 4 corresponding to the four FBP fuel types (C-2, C-4, C-5, and O-1) we used. Then FCDI_m, the fire control difficulty index for compartment m, is the weighted (by fuel type) average FCDI_{km} shown in eq. 2.

$$[2] \qquad \mathrm{FCDI}_m = \sum_{k=1}^{4} (C_{km}/100)\mathrm{FCDI}_{km}$$

Therefore, the FCDI is structured such that the FCDI of a compartment with a specified fuel composition will increase as its fire weather severity (as measured by the ISIs and BUIs observed at the fire weather stations in the compartment) increase or the fraction of the compartment that is covered with more volatile FBP fuel types that support more intense fires (e.g., C-2, boreal spruce) increases.

Assessing the level of protection delivered to a compartment

The term level of protection is commonly used to refer to the amount of suppression effort a forest fire management agency devotes to limiting the impact of fire in designated areas, but there are no simple measures of such efforts. One approach might be to identify activities that are thought to influence burned area and express the level of protection in terms of a vector that indicates the level of each of those activities (e.g., the number of prevention advertisements purchased; the area burned by prescribed burns conducted for hazard reduction purposes; and the number of fire fighters, transport helicopters, and airtankers hired for the season). A major difficulty with that approach is that fire management effort varies over both time and space as fire managers respond to spatial and temporal variations in weather, fire occurrence, fire behaviour, and values at risk. Each day they assess potential future fire occurrence and behaviour across their protected area and temporarily move resources from bases where they are not needed to deploy them close to areas where they believe potentially damaging fires might occur. They also supplement their base level suppression resources with resources borrowed from other forest fire management agencies. It is simply not feasible to document in sufficient detail what resources an agency had at its disposal each day and how it allocated those resources across its protected area.

We used the initial attack response time, the interval between the time a fire is reported and the time initial attack begins, as a surrogate measure of level of protection. Consider the simplest case, a circular fire burning in homogeneous vegetation in the absence of wind on flat terrain with its radius a linear function of time since ignition. If we assume the ability of the initial attack crew to contain the fire is a decreasing function of frontal fire intensity and the perimeter at the time control action begins, fire mangers will attempt to attack potentially destructive fires as soon as possible. When faced with more than one such fire, they should first attack the fire that poses the most significant threat. Response times are, not surprisingly, commonly used as emergency response system performance measures (see, for example, Larson and Odoni 1981).

A forest fire initial attack system can be viewed as a complex spatially distributed queueing system with fires as customers and initial attack units comprised of fire fighters and airtankers as servers (Martell 2001). The response time is the time the fire waits in the initial attack queue plus the travel time of the initial attack unit. The longer the response time, the more likely a fire will escape and burn over a large area. A rational fire manager would deploy his or her sup-

[9] Head fire intensity (kW/m) is a measure of the rate at which energy is being released by a fire per unit length of fire front per unit time. It is a product of the forward rate of spread of a fire (m/s), the amount of fuel consumed per unit area (kg/m^2), and the low heat of combustion of the fuel being consumed (kJ/kg) (Forestry Canada Fire Danger Group 1992, p. 38).

[10] Our decision to use head fire intensity was initially motivated by earlier unpublished work by P. Kourtz of the Canadian Forest Service and Booth (1983) who characterized the initial attack fire load in terms of the area of flame front that confronts an initial attack system.

Table 3. Variation in human- and lightning-caused fire activity and level of protection by fire management zone (FMZ) in the province of Ontario, 1976–1994.

					Initial attack response time (h)		
FMZ	Area (km^2)	Total no. of fires (1976–1994)	Avg. annual burned area (ha)	Avg. annual burn fraction	Mean	Median	SD
I	361 206	27 704	49 024	0.0014	2.48	0.67	12.32
M	112 193	3 153	20 143	0.0018	4.51	0.80	19.93
E	303 371	1 971	150 601	0.0050	14.94	1.88	51.61

pression resources so as to minimize the response time to potentially destructive fires and allow beneficial fires to wait, perhaps forever, for a response. Therefore, fire managers should be expected to increase their level of protection (or "buy more servers") and decrease their response times when losses are potentially high. Because average response times can be inflated by a very small number of very large somewhat anomalous response times, we used a more robust measure of central tendency, the median initial attack response time (expressed in hours) as our surrogate measure of level of protection (LOP).

Response time is a simple surrogate level of protection measure, but it is reasonable to assume that rational fire managers will expend more effort on prevention, detection, and the suppression of escaped fires in areas where fire poses a significant threat. Prevention, detection, initial attack, and escaped fire suppression efforts should be focused in high-value areas and be consistent with response times. This poses two important questions: (1) to what extent are response times consistent with the OMNR's stated fire management zoning scheme and (2) are burned areas correlated with initial attack response times?

Results

Table 2 is a statistical summary of the average annual lightning-caused fire burn fraction, initial attack response time, fire control difficulty, and fire weather severity varied in the 35 fire management compartments across the province of Ontario during our 1976–1994 study period. The average annual burn fraction varies over four orders of magnitude from 0.000 001 to 0.01. When measured in terms of their coefficients of variation, the FCDI and the LOP (measured in terms of the median initial attack response time) are almost identical and more variable than the fire weather severity (expressed in terms of ADSR).

Initial attack response time by fire management zone

The OMNR partitioned its protected area into three zones that vary with respect to level of protection. If they followed their policy and if response time is a measure of level of protection, the observed initial attack response times should be consistent with their policy — they should increase as one moves from the intensive protection zone through the measured protection zone to the extensive protection zone. We used the OMNR's historical fire report data to produce the estimates of the average annual burn fractions and initial attack response times by fire management zone (FMZ) for all (both human and lightning-caused) fires for the 1976–1994 period shown in Table 3.

The average initial attack response time or initial attack interval (IAI), the average elapsed time from the time a fire is first reported until the start of initial attack action, was 2.48 h in the intensive protection zone, 4.51 h in the measured protection zone, and 14.94 h in the extensive protection zone. The corresponding median initial attack response times were 0.67, 0.80, and 1.88 h. Those results indicate that the OMNR's initial attack system performance is compatible with its stated fire management objectives. The average annual burn fraction increased from 0.0014 in the intensive protection zone to 0.0018 in the measured protection zone and 0.0050 in the extensive protection zone. These results suggest that suppression is reducing area burned, but the apparent reduction in burned area associated with increased suppression effort may well be caused by other confounding factors and therefore merits further detailed investigation.

Having formulated a conceptual process model, our next step was to carry out an exploratory data analysis to support the development of an empirical model that can be used to relate a compartment's average annual burn fraction (BF), one of its most important fire regime attributes, to measures of its fuel, weather, and fire protection. We studied scatter plots and lowess curves (see Cleveland 1979) of BF versus the average annual FCDI, LOP, and the annual ADSR. Those plots suggested it is reasonable to model the BF as a linear function of FCDI, LOP, and ADSR. We then used the S-PLUS (Insightful Inc.) correlation analysis procedure (the cor function) to produce Pearson's correlation coefficients between BF, LOP, FCDI, and ADSR. The results are presented in Table 4.

Those results suggest that BF is correlated with all three covariates, but the correlation between BF and LOP (0.52) is a little larger than the correlation between lightning fire burn fraction (BF) and FCDI (0.41), which suggests that LOP may have a greater impact on burned area than FCDI. The correlation between BF and ADSR (0.10) suggests that ADSR alone has little impact on area burned. The correlation between FCDI and ADSR (0.23) indicates that the fire weather does have a modest impact on FCDI, which is not surprising given that fire danger rating indices are used to compute FCDI. Given the lowess scatter plots and these correlation coefficients, it is reasonable to fit a linear model to our data.

A linear regression model that relates average annual burned area to fuel, weather, and level of protection

We used ordinary least-squares (OLS) regression methods to fit the BF to the FCDI, LOP, and ADSR using the entire 35 compartment data set. We used the S-Plus version 7.0 lm

Table 4. Pearson's correlation analysis results.

	BF	LOP	FCDI	ADSR
BF	1.000	0.518	0.409	0.099
LOP	0.518	1.000	0.051	–0.278
FCDI	0.409	0.051	1.000	0.227
ADSR	0.099	–0.278	0.227	1.000

Note: BF, average annual burn fraction; LOP, median initial attack time; FCDI, fire control difficulty index; and ADSR, average daily fire severity rating.

Table 5. Model I: linear regression model for the average annual burn fraction (BF) as a function of the median initial attack time (LOP), fire control difficulty index (FCDI), and average daily fire severity rating (ADSR).

Variable	Parameter estimate	SE	*t* value	Prob (> |*t*|)
Intercept	–0.0046	0.0017	–2.7214	0.0106
LOP	0.0028	0.0007	3.8976	0.0005
FCDI	0.0001	0.0001	2.4585	0.0197
ADSR	0.0017	0.0014	1.2084	0.2360

Table 6. Model II: linear regression model for the average annual burn fraction (BF) as a function of the median initial attack time (LOP) and the fire control difficulty index (FCDI).

Variable	Parameter estimate	SE	*t* value	Prob (> |*t*|)
Intercept	–0.0028	0.0009	–3.2982	0.0024
LOP	0.0025	0.0007	3.6795	0.0009
FCDI	0.0002	0.0001	2.8332	0.0079

Table 7. Model III: linear regression model for the average annual burn fraction (BF) as a function of the median initial attack time (LOP) and the fire control difficulty index (FCDI) for the reduced protected area of Ontario (excluding polygon 9).

Variable	Parameter estimate	SE	*t* value	Prob (> |*t*|)
Intercept	–0.0030	0.0008	–3.5614	0.0012
LOP	0.0034	0.0008	4.0506	0.0003
FCDI	0.0001	0.0001	1.8586	0.0726

regression procedure (Venables and Ripley 2002) to estimate the parameters for model I described in Table 5.

The R^2 value for this model was 0.44. The F statistic was 8.159 and its p value was 0.0004. The LOP was significant (p = 0.0005) as was FCDI (p = 0.0197), but ADSR proved not to be statistically significant (p = 0.2360). Therefore, we removed the ADSR from our model and fitted a linear model to FCDI and LOP alone to produce the model II results presented in Table 6. The R^2 value for this model decreased slightly to 0.41. The F statistic was 11.35 and its p value was 0.0002. The LOP remained statistically significant (p = 0.0009) and FCDI (p = 0.0079) increased in significance.

Hat matrix influence tests (see Belsley et al. 1980) indicated that compartment 9 was very influential and compartment 6 was also influential, but much less so. Compartment 9 is a 162 258 km^2 compartment that lies in the Hudson Bay Lowlands forest section, which has a BF of 0.000 64. Unfortunately, since the method we used to determine if what Bickerstaff et al. (1981) reported as spruce was lowland or upland spruce classified all of the spruce in compartment 9 as lowland spruce, its FCDI was 0. Its LOP (as measured by the median initial attack time interval) was 2.17, the largest LOP observed. Clearly compartment 9 should have a positive FCDI, but the methodology we used to assess FCDI is not suitable for areas dominated by lowland spruce, which does burn under some circumstances. The inclusion of compartment 9 in the data set may produce an overestimate of the impact of fire suppression on burned area, as its inclusion would implicitly attribute all of the burned area in compartment 9 to its low level of protection. Therefore, we decided to exclude compartment 9 from our analysis. We then used the S-Plus 7.0 lm procedure without compartment 9 (with 34 observations) and obtained the model III results given in Table 7.

The R^2 value increased very slightly to 0.46. The F statistic was 13.44 and its p value was 0.0001. The LOP remained significant (p = 0.0003), but FCDI became less significant (p = 0.0726). Compartment 6 became more influential but not unreasonably so. However, the Normal quantile–quantile plot of residuals shown in Fig. 3 indicates our errors are not normally distributed.

Residual diagnostics

The use of linear regression models is based on the assumption that the error terms are independently and identically distributed as Normal random variables with a mean of zero and a constant variance. The distribution of residuals presented in Fig. 3 clearly indicates that the assumption of normality is not reasonable for our BF model. Scatter plots of the residuals exhibited a strong increase in their variance when plotted against both FCDI and LOP. Therefore, we used the Box–Cox procedure (Box and Cox 1964) implemented in S-Plus to identify an appropriate transformation of BF to stabilize the variance. The maximum likelihood estimate of the Box–Cox parameter, λ, was 0.05, very close to 0, which indicated a log transformation of the BF should be used.

Scatter plots of log(BF) versus FCDI and LOP indicated it was reasonable to assume that log(BF) is a linear function of both of those two covariates, so we proceeded to fit model IV shown in Table 8. The R^2 value decreased very slightly to 0.44. The F statistic was 12.38 and its p value was 0.0001. The LOP remained very significant (p = 0.0014) and FCDI became more significant (p = 0.0290). The Normal quantile–quantile plot presented in Fig. 4 indicates the assumption of normality is reasonable for the log-transformed model. In addition, scatter plots of the log-transformed model residuals indicated that they do not vary significantly as the FCDI and LOP vary. We noted that the residuals may decrease somewhat towards the upper end of the range of LOP, but there are so few large LOP observations that it is difficult to determine if that is in fact the case. Given these results, it is reasonable to use a log-transformed model.

Fig. 3. Normal quantile–quantile plot of the residuals for model III, the linear regression model of the average annual burn fraction (BF) as a function of the median initial attack time (LOP) and the fire control difficulty index (FCDI) for the reduced protected area of Ontario (excluding polygon 9).

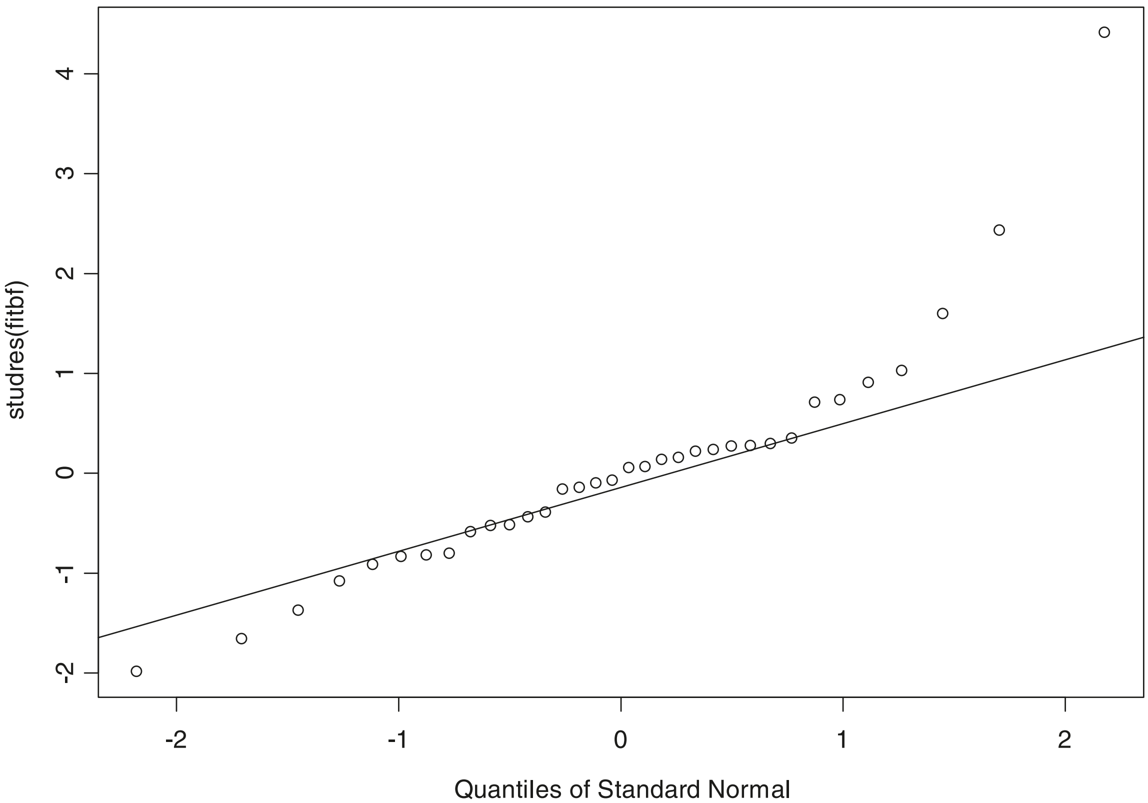


Table 8. Model IV: linear regression model for the logarithm of the average annual burn fraction (BF) as a function of the median initial attack time (LOP) and the fire control difficulty index (FCDI) for the reduced protected area of Ontario (excluding polygon 9).

Variable	Parameter estimate	SE	*t* value	Prob (> |*t*|)
Intercept	–14.6914	1.0911	–13.4653	<0.0001
LOP	3.8688	1.0996	3.5184	0.0014
FCDI	0.1826	0.0797	2.2905	0.0290

Table 9. Model V: spatial lag model with the logarithm of the average annual burn fraction (BF) as a linear function of the median initial attack time (LOP), the fire control difficulty index (FCDI), and the logarithm of the average annual burn fractions in neighbouring polygons for the reduced protected area of Ontario (excluding polygon 9).

Variable	Parameter estimate	SE	*t* value	Prob (> |*t*|)
Intercept	–10.3828	2.4138	–4.3014	<0.0001
LOP	2.9433	1.0800	2.7252	0.0064
FCDI	0.1572	0.0739	2.1263	0.0335

Dealing with spatial autocorrelation

Our use of linear regression models is based on the assumption that the average annual fraction of the area burned in each of the 34 compartments we studied is independent of what happens in the other compartments. This assumption is violated if there is spatial autocorrelation in the residuals. In the presence of such spatial autocorrelation, an OLS model could produce biased estimates of model parameters and lead to incorrect inference concerning the statistical significance of covariates (see, for example, Waller and Gotway 2004 and Kutner et al. 2004).

Figure 5 is a map of Ontario that shows the residuals obtained from fitting our log(BF) model. The similarities in residual values for neighbouring polygons suggest there may be some spatial autocorrelation in our residuals. We used the R lm.morantest[11] for spatial autocorrelation in residuals and found that the Moran I statistic standard deviate was 1.7796 with a p value of 0.0376, which indicates there is some spatial autocorrelation in the residuals that should be investigated. One way of dealing with such problems is to fit a spatial lag model (Anselin 2001) of the form

$$\boldsymbol{y} = \rho \mathbf{W}\boldsymbol{y} + \mathbf{X}\boldsymbol{\beta} + \varepsilon \qquad [3]$$

where $\boldsymbol{y}$ is an $n \times 1$ vector, ρ is the spatial autocorrelation coefficient, $\mathbf{W}$ is a spatial weight matrix that describes the neighbourhood structure of the area being studied, $\mathbf{X}$ is an $n \times k$ matrix of exogenous covariates, $\boldsymbol{\beta}$ is the corresponding vector of regression coefficients, and ε is a vector of

[11] We used the lm.morantest, which is available in the spatial dependence (spdep) package (Bivand et al. 2006) for the R software environment for statistical computing and graphics (R Development Core Team 2006).

Table 10. Variation in the average annual burn fraction (BF), fire control difficulty index (FCDI), median initial attack time (LOP), and average daily fire severity rating (ADSR) in the Northern Coniferous forest section.

Fire management compartment	FMZ	Area (km^2)	FCDI	LOP	ADSR	BF
6	E	123 119	15.98	1.87	1.13	0.0100
12	M	26 338	17.41	1.00	1.29	0.0059
13	I	17 375	16.43	0.82	1.17	0.0021

Note: FMZ, fire management zone.

Table 11. Spearman's rank correlation analysis of the Central Plateau forest section.

Fire management compartment	FMZ	Area (km^2)	FCDI	LOP	ADSR	BF
19	M	1 554	14.39	0.58	0.70	0.000 014
16	E	3 503	14.39	1.17	0.70	0.000 070
62	I	60 102	15.69	0.78	0.92	0.000 137
30	M	7 264	17.81	0.85	1.30	0.000 260
15	M	13 408	15.37	1.40	0.87	0.000 608
25	M	1 602	13.16	1.42	0.67	0.001 919
11	E	14 491	15.66	1.48	0.90	0.005 376

Note: FMZ, fire management zone; BF, average annual burn fraction; FCDI, fire control difficulty index; LOP, median initial attack time; and ADSR, average daily fire severity rating.

random error terms. We used a queen neighbourhood structure. This means that any two compartments that share at least one common point on their boundaries are classified as neighbours and the $w_{i,j}$ element of **W** was set equal to 1 if, and only if, compartment *i* was a neighbour of compartment *j*, otherwise it was set equal to 0. We then used the lagsarlm procedure in the R spdep library to fit a spatial lag model to the data and obtained the results shown in Table 9.

The estimated value of ρ (0.358) with a *p* value of 0.0544 does indicate a need to deal with the spatial autocorrelation in the residuals. In the spatial lag model, the statistical significance of FCDI is largely unchanged ($p = 0.0335$), but the statistical significance of LOP decreases ($p = 0.0064$). The Lagrange Multiplier test for residual autocorrelation test statistic is 0.9448 with a *p* value of 0.3311, which indicates the spatial lag model has addressed our spatial autocorrelation concerns. The net result is that both FCDI and LOP are statistically significant, but (based on the *p* values) LOP is more significant than FCDI. These results support our hypothesis that fuel, weather, and level of protection influence the area burned by forest fires in the province of Ontario.

The results of our regression analyses indicate that both our FCDI and LOP are very significant, but the compartment with the highest fire control difficulty is the 7264 km^2 compartment 30, which lies in the central portion of the fire region. In fact, the compartments (6, 12, and 13) in which fires tend to be most difficult to control tend to fall in the northwest quadrant of the fire region and receive low levels of protection. That superficially paradoxical situation is a consequence of the fact that those compartments generally contain fewer values at risk and therefore receive relatively less protection than some lower FCDI compartments.

Controlling for fuel and weather

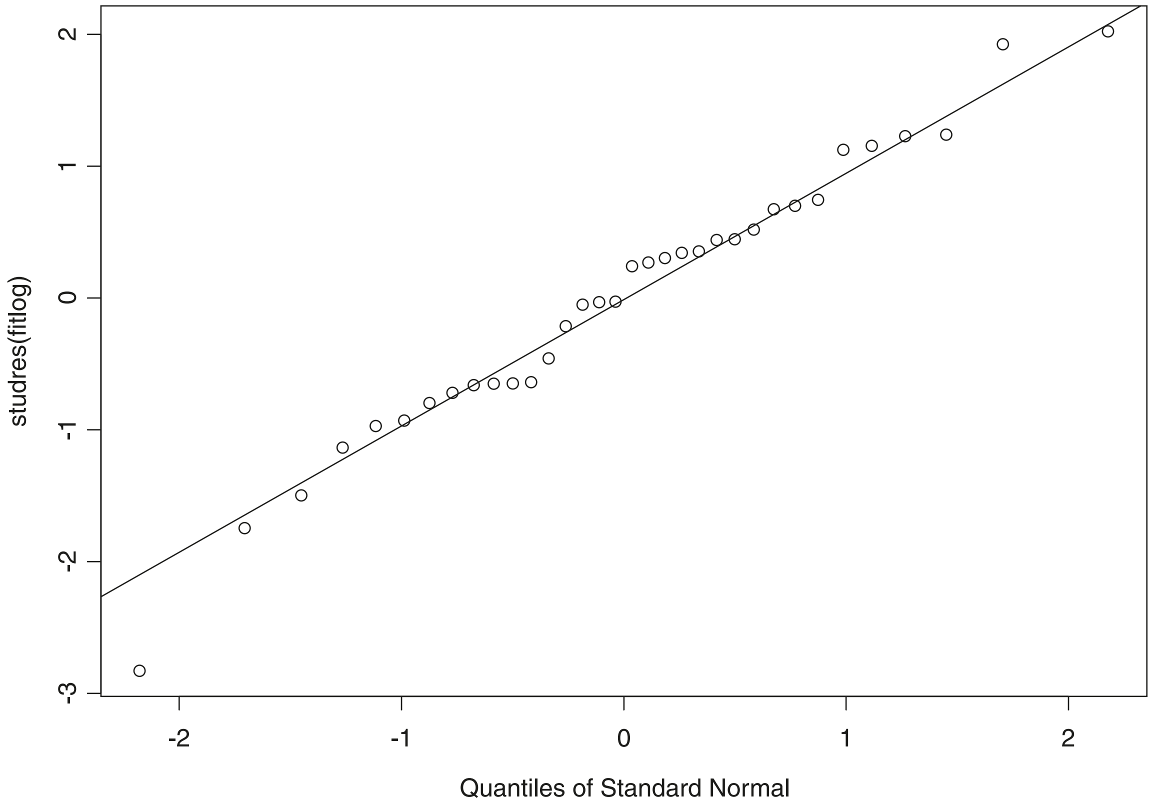
The primary objective of this study was to assess the extent to which fire suppression, weather, and vegetation contribute to spatial variation in the BFs across Ontario. However, vegetation and weather vary much more than LOP across Ontario. Consider the 34 compartments other than compartment 9. The FCDI, our integrated measure of fuel and weather, averaged 10.50 but ranged from 2.32 in compartment 92, a 12 801 km^2 compartment in the intensive protection zone in the Algoma forest section, to 17.81 in compartment 30, a 7264 km^2 compartment, which lies in the measured protection zone in the Central Plateau (CP) forest section. The largest FCDI is therefore 7.7 times as large as the smallest FCDI. Therefore, we decided to examine more closely the Northern Coniferous (NC) and CP forest sections that together comprise 268 756 km^2 or 43.7% of the 614 512 km^2 reduced fire region.

The 166 832 km^2 NC forest has been partitioned into three compartments based on the OMNR's level of protection zone as described in Table 10. The ADSR and FCDI are reasonably stable across all three compartments, although compartment 12 has the largest values of both attributes. Both the annual burn fraction and the response time decrease as we move from the extensive protection zone through the measured protection zone to the intensive protection zone. These results suggest that LOP is more significant than FCDI in the NC forest section.

We then studied the seven compartments that lie within the CP forest section, a 101 924 km^2 forest section that spans all three fire management zones. The procedure we used to overlay forest sections and fire management zones partitioned the CP forest section into the two extensive (E) fire management compartments, four measured (M) fire management compartments, and one intensive (I) fire management compartment described in Table 11. This happenstance presents a unique opportunity to explore the impact of LOP on burned area in an area over which fuel and weather should not exhibit significant variation.

We began by determining the extent to which fuel and

Fig. 4. Normal quantile-quantile plot of the residuals for Model IV, the linear regression model of the logarithm of the average annual burn fraction (BF) as a function of the median initial attack time (LOP) and the fire control difficulty index (FCDI) for the reduced protected area of Ontario (excluding polygon 9).



weather, as measured by the FCDI, actually vary across those seven compartments. The mean FCDI in the seven compartments in the CP is 15.21 and its SD is 1.46. This results in a coefficient of variation (CV) of the FCDI within the CP forest section of 0.096. The mean LOP in the seven compartments in the CP forest section is 1.096 and its SD is 0.361, resulting in a CV of 0.330, which is much larger than that of the FCDI. The CP forest section is therefore (as expected) relatively homogeneous with respect to the FCDI, but variable with respect to its LOP. Therefore, it is well-suited for assessing the impact of fire suppression alone on area burned.

The Spearman's rank correlation between the burn fraction and FCDI in the CP is 0.09, which indicates there is no significant relationship between those two variables in that area. The Spearman's rank correlation between the burn fraction and LOP (as measured by the median initial attack interval) was 0.89. These results indicate that in the CP forest section, the burn fraction increases as the initial attack interval increases, an indication that LOP does indeed influence area burned in that particular forest section.

Discussion

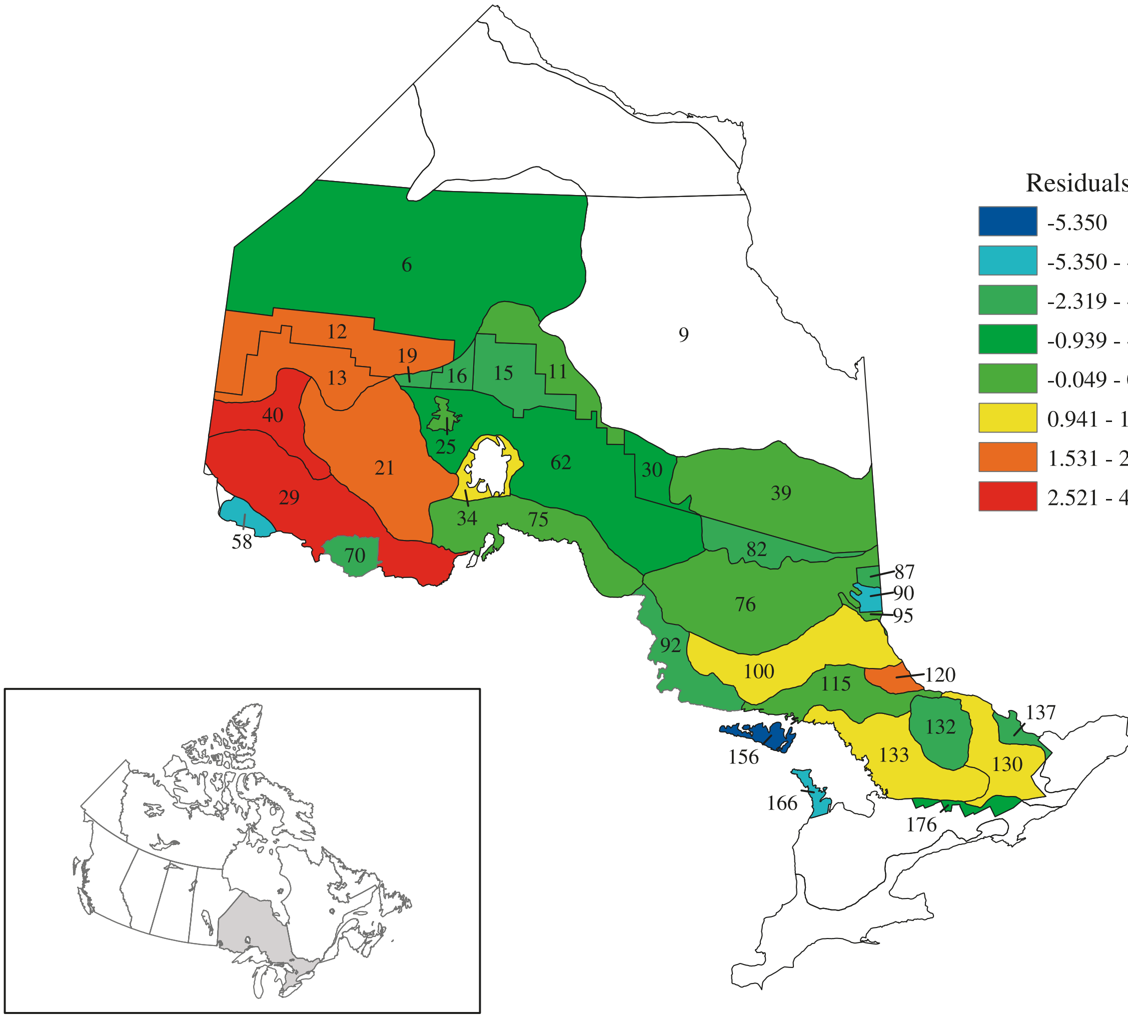
We have developed and applied a methodology that can be used to relate spatial variation in lightning-caused fire regimes in Ontario to vegetation, weather, and the level of fire protection. We used the first two variables to develop a FCDI and we used the average initial attack response time as a level of fire protection index. Both variables proved to be statistically significant. Our results support the belief that fire suppression does reduce area burned in boreal forests. Furthermore, they support Ward and Tithecott's (1993) conclusion that fire suppression has had a significant impact on area burned in Ontario.

We assumed that lightning storm activity does not vary by fire management compartment. Maps of thunderstorm day frequency per annum and during the month of July (Hare and Hay 1974, p. 98) indicate that lightning activity generally decreases as one moves in a northeasterly direction in northern Ontario, which lends credence to our finding that increased fire suppression effort (LOP) contributes to decreased fire activity (fraction of the protected area burned). Our methodology could be enhanced by incorporating lightning activity in our model. The OMNR and many other forest fire management agencies have established large networks of lightning locating devices that provide data, which should prove to be quite valuable in that regard.

We used Rowe's (1972) forest classification system to facilitate the application of our methodology, and we believe it can be used to assess the impact of fire suppression on burned area in other jurisdictions. We intentionally used these very broad measures of forest vegetation to enhance the portability of our methodology. Modern satellite remote sensing and image-processing technologies can be used to produce much better measures of forest vegetation that should enhance our FCDI.

Finally, we recognize that the average initial attack re-

Fig. 5. Map of the residuals resulting from fitting model IV, the linear regression model of the logarithm of the average annual burn fraction (BF) as a function of the median initial attack time (LOP) and the fire control difficulty index (FCDI) for the reduced protected area of Ontario (excluding polygon 9).



sponse time is a crude measure of the level of fire protection that does not account for fire detection efforts or the fact that the OMNR does not dispatch the same initial attack force to all fires. The OMNR does document many aspects of its detection program and fire reports contain some information that describe the size and composition of the initial attack force dispatched to each fire. Such information could be used to improve on the average initial attack response time as a level of protection measure.

In Ontario, forest fires are reported by the public (unorganized detection) and by OMNR detection observers that fly designated fire detection patrol routes (organized detection). Since the OMNR allocates its fire management resources according to its fire management objectives, which vary by zone and population levels, and land use activities also vary by zone, it is reasonable to assume that fire detection rates (e.g., the probability that a fire will be detected and reported to the OMNR) can, and probably does, vary by zone. Unfortunately, that variation is difficult to quantify and has yet to be documented. However, since (*i*) we are primarily interested in burned area rather than fire numbers and mean fire size, (*ii*) most of the area that is burned is burned by large fires, and (*iii*) it is reasonable to assume that most if not all large fires are detected in all zones, we believe it is reasonable to ignore zonal variation in fire detection effectiveness when investigating burned area.

Fire suppression can reduce area burned by means of initial attack, which reduces the number of large fires, and by reducing the size of large fires that escape initial attack. Cumming (2005) studied lightning fires in a 86 000 km^2 boreal mixedwood forest region of Alberta that is relatively homogeneous with respect to "climate, vegetation, [and] physical geography" over the 31 year period from 1968 to 1998. He did not develop an empirical measure of fire suppression effort but assumed it increased at some constant rate over the study period. He also identified 1983 as the year in which the Alberta Sustainable Resources Development Department introduced a new "presuppression preparedness system" that had the potential to increase initial attack effectiveness. He modelled the probability that fires escaped initial attack (i.e., grew to a final size >3 ha) or became big (a final size >200 ha) as a function of fire suppression effort (as measured by time), strategy, and other covariates. He concluded that the increase in initial attack effectiveness was largely attributable to the 1983 change in policy and stated that "fire suppression by initial attack has had a nontrivial impact on area burned [in the boreal forest region of Alberta] over recent decades... and therefore fire suppression can significantly reduce area burned in boreal forests." Our results are consistent with Cumming's (2005) findings, but we assessed the net impact of both the initial attack and large fire management subsystems. Future studies should be directed to assessing the performance of those two subsystems independently.

Our methodology can be used to support ecosystem management approaches to forest management in Ontario. Given the significant role fire plays in many Canadian forest ecosystems, land managers should consider explicitly what fire regimes might be appropriate for each of their management compartments that may differ with respect to the attributes of their ecosystem processes. Our methodology could then be used to help increase the likelihood that the fire management program "delivers" burn fractions that are compatible with those ecosystem specific fire regimes.

Our model was developed to relate large-scale variation in burned area to the level of protection, weather, and vegetation across Ontario and can be used for strategic planning purposes. It can also be used to assess the potential impact of a warming climate and related changes in vegetation on burned area. Climate change weather scenarios could be used to generate fire weather scenarios and coupled with a dynamic global vegetation model (DGVM) to predict how the vegetation in each compartment will change over time. The projected weather and vegetation data could then be used to project how the FCDI would vary over time and our logistic model used to predict the burned area response that would ensue.

Bond and Keeley (2005) explored the similarities between fire and herbivory from a global perspective and in their concluding sentence they referred to "the ubiquitous overlay of human impacts on fire regimes" and stressed the need for a "greater understanding of fire as a globally important consumer." It's obvious to most observers that changes in demographic patterns, land use activities, climate, and fire suppression are influencing fire regimes across much of the boreal forest region of Canada and that we have altered a large tract of forest in very significant ways. We can change the way we manage fire far more quickly and easily than we can mitigate our other impacts on this region. It is time to move beyond the debate about the extent to which fire suppression has altered the fire regime of the boreal forest and focus on the development and implementation of sound ecosystem management strategies for the region.

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