21562202d, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Large forest fires in Canada, 1959–1997

B. J. Stocks,[1] J. A. Mason,[1] J. B. Todd,[2] E. M. Bosch,[1] B. M. Wotton,[1] B. D. Amiro,[2] M. D. Flannigan,[2] K. G. Hirsch,[2] K. A. Logan,[1] D. L. Martell,[3] and W. R. Skinner[4]

Received 8 February 2001; revised 22 August 2002; accepted 28 August 2002; published 20 December 2002.

[1] A Large Fire Database (LFDB), which includes information on fire location, start date, final size, cause, and suppression action, has been developed for all fires larger than 200 ha in area for Canada for the 1959–1997 period. The LFDB represents only 3.1% of the total number of Canadian fires during this period, the remaining 96.9% of fires being suppressed while <200 ha in size, yet accounts for ~97% of the total area burned, allowing a spatial and temporal analysis of recent Canadian landscape-scale fire impacts. On average ~2 million ha burned annually in these large fires, although more than 7 million ha burned in some years. Ecozones in the boreal and taiga regions experienced the greatest areas burned, with an average of 0.7% of the forested land burning annually. Lightning fires predominate in northern Canada, accounting for 80% of the total LFDB area burned. Large fires, although small in number, contribute substantially to area burned, most particularly in the boreal and taiga regions. The Canadian fire season runs from late April through August, with most of the area burned occurring in June and July due primarily to lightning fire activity in northern Canada. Close to 50% of the area burned in Canada is the result of fires that are not actioned due to their remote location, low values-at-risk, and efforts to accommodate the natural role of fire in these ecosystems. The LFDB is updated annually and is being expanded back in time to permit a more thorough analysis of long-term trends in Canadian fire activity. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3324 Meteorology and Atmospheric Dynamics: Lightning; 9350 Information Related to Geographic Region: North America; 9810 General or Miscellaneous: New fields (not classifiable under other headings); *KEYWORDS:* boreal forest, ecozones, wildfire, distribution, suppression, fire attributes

Citation: Stocks, B. J., et al., Large forest fires in Canada, 1959–1997, *J. Geophys. Res.*, *107*, 8149, doi:10.1029/2001JD000484, 2002. [printed *108*(D1), 2003]

1. Introduction

[2] Fire has been a dominant disturbance regime in Canadian forests since the last Ice Age. This is particularly true in Canada's vast boreal forest region where fire is a process critical to the very existence of primary boreal species such as pine, spruce, and aspen, and is responsible for shaping landscape diversity, and influencing energy flows and biogeochemical cycling. The physiognomy of Canadian boreal forests is strongly tied to the fire regime and requires periodic high intensity, stand-replacing fires to exist [e.g., *Kasischke and Stocks*, 2000]. The fire regime is comprised of fire frequency, size, intensity, seasonality, type and severity, and the ecological importance of some of these components has been elucidated by *Malanson* [1987], *Whelan* [1995], and *Weber and Flannigan* [1997]. Fire frequency affects Canadian forests through the interruption or termination of tree/stand life cycles. Fire size determines landscape patchiness and also affects effective regeneration distances. Fire intensity represents the energy released during a fire, and can vary greatly both between and within fires depending on fuel type and loading, topography and meteorological influences. The season of the year in which fire occurs is one of the determinants of post-fire successional pathways, affects fire intensity through seasonal differences in surface and crown fuel moisture contents, and has a pronounced effect on the structure of post-fire ecosystems and landscapes. Fire type refers to crown, surface and ground fires, which are largely controlled by fire intensity and fuel characteristics (structure, load and moisture) and weather. Fire severity is a measure of fuel consumption, primarily the depth of burn in surface soil organic layers and is therefore another important controlling factor of post-fire ecosystem structure and function.

[3] In the early 1990s global biomass burning became recognized as a major perturbation to atmospheric chemistry, with resultant impacts on the earth's physical and chemical climate [*Levine*, 1991, 1996]. Although the initial focus was on biomass burning in tropical regions, partic-

[1]Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, Ontario, Canada.
[2]Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, Canada.
[3]Faculty of Forestry, University of Toronto, Toronto, Ontario, Canada.
[4]Meteorological Service of Canada, Downsview, Ontario, Canada.

Copyright 2002 by the American Geophysical Union.
0148-0227/02/2001JD000484

ularly in association with population pressure-driven land use change, this effort also drew attention to the formidable task of quantifying vegetation fires at a global scale. In this context the 1990s brought an increased emphasis on determining the extent and impact of boreal fires [*Stocks*, 1991]. The recent scientific consensus indicates that climate change impacts will be most significant in the carbon-rich boreal zone. This conclusion, coupled with the realization that fire activity is extremely sensitive to weather/climate [*Flannigan and Harrington*, 1988; *Johnson*, 1992; *Swetnam*, 1993], and that carbon dynamics in this region are driven largely by fire [*Kurz and Apps*, 1999], suggests that climate change will lead to increasing fire occurrence and severity in the boreal zone, with resultant impacts on terrestrial carbon cycling and storage. Recent modeling of potential future fire activity using General Circulation Models suggests that significant increases in fire occurrence and severity are likely in west-central Canada and Siberia [*Flannigan et al.*, 1998; *Stocks et al.*, 1998; *Flannigan et al.*, 2000]. Increases in fire season length [*Wotton and Flannigan*, 1993] and lightning activity [*Price and Rind*, 1994] are also anticipated. These interactions between fire, climate change and carbon buttress the need to develop spatially-explicit databases of boreal fire in Canada, Russia and Alaska. This is particularly true in the post-Kyoto world, where carbon accounting and negotiations on emissions will be conducted in a transparent and mutually-informed manner. Disturbance by fire is strongly recognized as affecting global sources and sinks of carbon dioxide, such that accurate estimates of area burned are important for future international agreements and accounting. Russian fire statistics have not been accurately recorded in the past, and Russian fire activity post-1980 is currently being reconstructed through the use of remote sensing [e.g., *Cahoon et al.,* 1994, 1996; *Stocks et al.*, 1996a; *Kasischke et al.,* 1999]. Canadian and Alaskan fire statistics had been recorded for many decades, with a spatial database of large Alaskan fires post-1940 being recently produced [*Kasischke*, 2000]. However the spatially- and temporally-explicit databases required to accurately illustrate fire activity in Canada had never been developed.

[4] Toward this end, an effort was initiated in 1989 to develop a database of all large fires (fires >200 hectares in area) in Canada. Since, on average, only ~3% of all Canadian fires exceed 200 ha in size, yet these fires account for ~97% of the area burned nationally [*Stocks*, 1991], a relatively small spatially- and temporally explicit database could be developed and used to represent and illustrate overall national fire area burned impacts quite adequately. The Canadian Large Fire Data Base (LFDB) has been used to estimate carbon loss from Canadian fires, both for the 1980s [*Stocks et al.*, 1996b] and for the 1959–1999 period [*Amiro et al.*, 2001a]. This paper summarizes the development of the LFDB over the past decade, and provides analyses of the area burned, frequency, size distribution, cause, seasonality for the post-1959 period aimed at generating a landscape-level picture of fire activity in Canada.

[5] National forest fire statistics have been compiled since 1918 in Canada, but an extensive analysis of this record is compromised by the fact that large regions of Canada were not monitored prior to satellite coverage in the early 1970s. Deficiencies in the Canadian record were emphasized in *Murphy et al.* [2000], with the acknowledgment that many provinces did not document fires in remote northern regions (British Columbia, Alberta, Saskatchewan, Manitoba, Ontario and Quebec) prior to the 1950s and 1960s, and that the Northwest Territories and Newfoundland only began fire record-keeping in the 1950s. Official Canadian fire occurrence and area burned statistics post-1920 have been analyzed previously [*Van Wagner*, 1988; *Stocks*, 1991; *Stocks et al.*, 2001] with the general observation that, using decadal averages, recorded fire numbers have increased steadily over the last eight decades to ~8,000 fires annually during the 1990s, while documented area burned decreased from the 1920s through the 1950s, and has increased continually since, averaging ~2.75 million hectares annually during the 1990s. The incompleteness of the Canadian fire record from 1920 to 1970 remains a barrier to a thorough analysis of longer-term trends in Canadian fire activity. Bearing in mind the deficiencies of the record prior to the 1970s, it is evident that the annual area burned in Canada fluctuates greatly from year-to-year, primarily driven by the frequency and geographical extent of extreme fire weather/danger conditions, but it is also apparent that lower area burned statistics existed prior to 1970. Given these uncertainties, the sudden increase in area burned since that time cannot be positively seen as a sign that fire danger levels are generally increasing, or that a definitive climate change signal is involved. Increases in fire activity in recent decades are likely the result of expanded forest use in combination with an increased fire detection/monitoring capability. Regardless, the annual area burned in Canada continues to fluctuate significantly from year-to-year, and has varied by more than an order of magnitude (~0.3 million ha in 1978 to 7.5 million ha in 1995) over the last three decades when coverage and documentation was reasonably complete [*Stocks et al.*, 2001]. Recent studies of area burned trends clearly showed the importance of large fires in Canada [*Harrington*, 1982; *Weber and Stocks*, 1998]. *Harrington et al.* [1983] found that components of the Canadian Fire Weather Index (FWI) System [*Van Wagner*, 1987] were correlated to monthly provincial area-burned in Canada 1953–80. *Flannigan and Harrington* [1988] found that long periods with daily precipitation less than 1.5 mm of rain were correlated with monthly provincial area-burned in Canada 1953–80. Area burned by forest fire is determined by a complex set of variables including the extent of the forest, the topography, the presence or absence of lakes and roads, fuel characteristics, season, latitude, fire management organizational size and efficiency, fire site accessibility, the number of simultaneous fires and the weather.

[6] Organized forest fire management began in Canada in the early decades of the 1900s after numerous catastrophic wildfires, and with the initial philosophy that fire was destructive and should be eliminated to enhance public safety, protect property, and permit proper forest management. Expanded use of the Canadian boreal zone, for both industrial and recreational purposes, resulted in a concurrent increase in both fire occurrence and the fire management capability mobilized to address this problem. Canadian provincial and territorial fire management agencies are currently among the most modern worldwide and, through fire prevention and suppression, have generally succeeded

21562202d, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

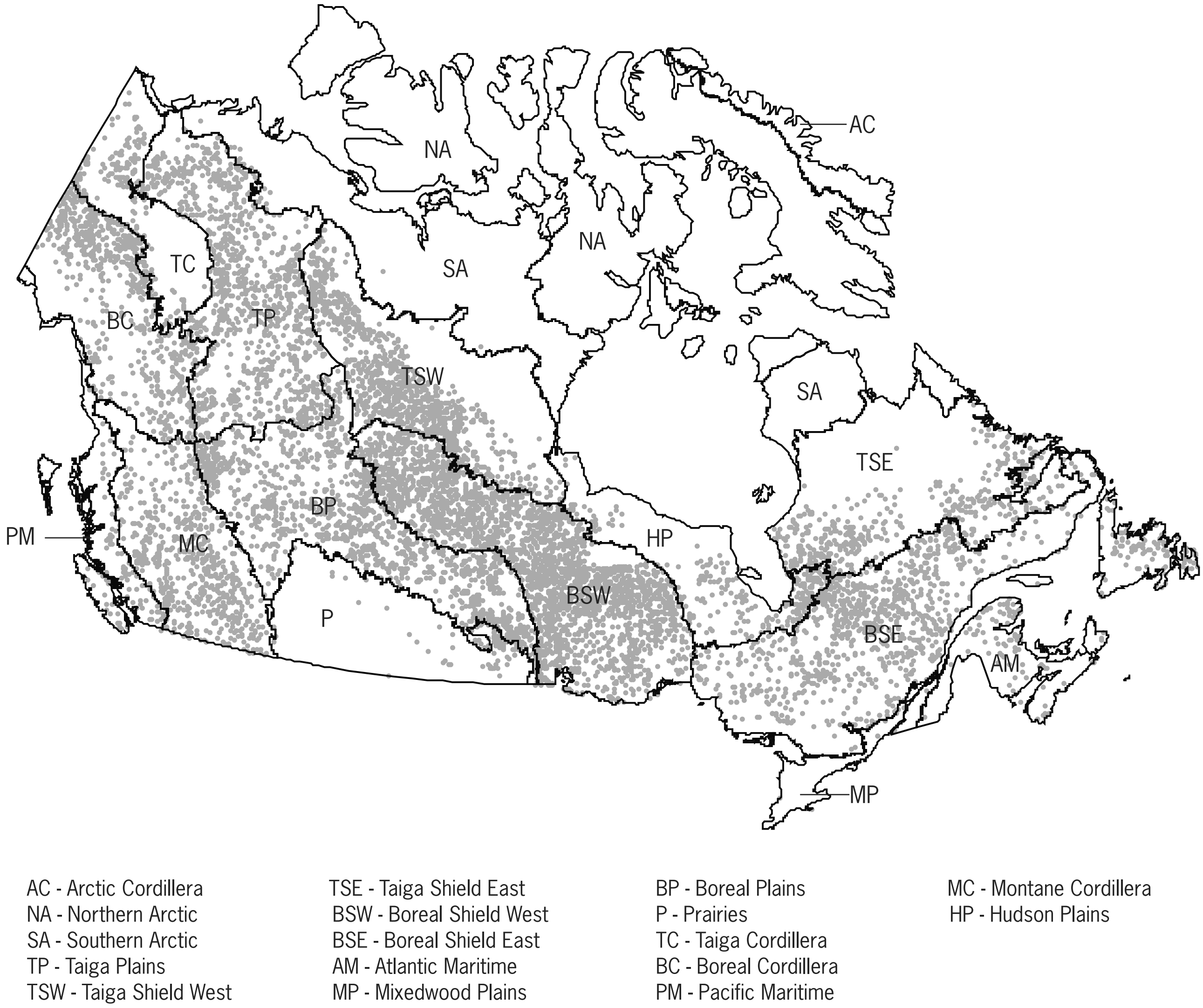

Figure 1. Ecozone boundaries and geographical distribution of 1959–1997 LFDB fires across Canada.

in progressively reducing fire impacts in intensively protected forests over the past 70 years [*Stocks and Simard*, 1993]. However, the growing realization that excluding fire is neither economically possible nor ecologically desirable, coupled with constrained budgets and a growing awareness of the benefits of natural fire to Canadian forest ecosystems, is leading toward a balanced approach to fire management that weighs the protection of human life, property and industrial timber supply against the necessity of periodic wildfire.

2. Methods

2.1. Database Construction

[7] Beginning in 1989, individual wildfire reports for fires larger than 200 ha were collected from all Canadian fire management agencies (ten provincial, two territorial, and Parks Canada) for the post-1980 period. Over a period of time these fires were digitized and mapped in a Geographical Information System (GIS), with the database containing spatial polygons for each fire, along with supporting attribute information (location, start date, final fire size, cause, and suppression action). This database was used in an analysis of the distribution and characteristics of large Canadian fires during the 1980s [*Stocks et al.*, 1996b].

[8] In recent years the LFDB has been expanded to include all large fires back to the start of record-keeping for all Canadian agencies. In some cases this extends as far back as 1918, but a continuous national record is only available from the 1950s when statistical record-keeping began in Newfoundland and the Northwest Territories. Maps for these pre-1980 fires are still in the process of being digitized, and a complete polygon record is some time away. However, attribute information is complete for all LFDB fires, and permits a national analysis for the 1959–1997 period.

[9] It is recognized that the LFDB is not without some limitations. Estimates of the area burned by each fire are the result of aerial mapping or analysis of satellite imagery, and it is thought that more recent fire size estimates tend to be more accurate, taking into account the larger unburned islands within fires, and providing more detailed perimeter mapping. As mentioned earlier, many fires in more remote northern regions of some jurisdictions (particularly Quebec,

21562202d, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Table 1. Area Burned (ha) by LFDB Fires by Ecozone and Years for the 1959–1997 Period, Average Area Burned (AAB), and Percent Annual Area Burned (PAAB) by Ecozones

Year	Southern Arctic	Taiga Plains	Taiga Shield West	Taiga Shield East	Boreal Shield West	Boreal Shield East	Atlantic Maritime	Mixed Wood Plains	Boreal Plains	Prairies	Taiga Cordillera	Boreal Cordillera	Pacific Maritime	Montane Cordillera	Hudson Plains	Total
1959	0	76710	1360	0	14623	25601	23735	0	55913	0	8496	43342	0	28343	0	278124
1960	0	11203	37923	0	331073	27387	29940	445	34495	243	7432	1777	2596	100435	0	584950
1961	0	184872	178264	8015	737203	417927	2002	0	750301	39783	0	161534	14363	257666	6219	2758149
1962	0	19952	2245	0	11775	103707	0	4047	58317	364	9058	13110	1010	3272	93242	320099
1963	0	15668	5052	1295	56370	37319	2158	940	14324	11987	5606	11827	1174	1028	606	165353
1964	0	5430	178860	513	658954	91352	366	212	167501	11162	0	906	0	0	18226	1133482
1965	0	27544	486	0	5528	5428	1306	217	72322	4525	5538	48178	5005	22300	0	198377
1966	2592	129833	98774	0	16874	10319	0	364	25318	324	1015	197663	473	682	0	484231
1967	0	39206	5759	23829	138170	89425	0	0	64920	3895	10278	114144	8925	69509	0	568061
1968	35148	189501	4065	24710	16297	465990	4107	0	471358	4592	0	16831	501	3381	12944	1249425
1969	0	493047	23053	6954	84127	1158	557	0	31247	0	124064	614521	2205	19561	0	1400493
1970	0	71015	248674	21142	796076	6696	1012	0	212349	246	0	24303	2402	44881	0	1428795
1971	0	423522	462353	0	90230	240703	0	0	212799	1389	33816	315490	6565	101386	27850	1916103
1972	4147	215335	36345	10951	192038	54633	0	0	58849	640	26614	42899	3398	2354	75621	723825
1973	1260	202233	272697	85846	386532	3203	0	0	25739	2080	0	869	672	24563	6066	1011759
1974	1367	15635	8344	103337	673146	46918	0	0	17819	5200	1799	1631	348	9921	6368	891834
1975	0	490196	95721	21316	126889	191648	386	859	7961	600	17250	10559	0	2471	4937	970795
1976	900	298088	388810	163611	630201	508251	0	0	74718	910	2084	55637	0	752	19871	2143835
1977	0	160567	131055	243	442724	50797	0	0	201836	38180	264163	47427	0	1144	29785	1367919
1978	0	7081	77380	1036	96366	6473	908	0	23430	243	4655	31208	5302	7251	0	261334
1979	8100	1162904	1477906	1003	255508	33621	0	0	146355	445	6320	2618	1841	8678	1405	3106704
1980	0	1088012	374726	8142	1882570	19459	2631	0	1177379	53993	2415	157366	0	6650	7522	4780864
1981	0	1271717	211647	58082	2265983	93869	0	0	2059778	1800	0	48608	862	15996	60661	6089002
1982	0	464511	94913	26267	66654	12461	5339	0	481812	0	26226	526219	785	9448	0	1714636
1983	0	219578	15698	316737	556624	629838	590	0	25069	3695	13090	75757	0	20909	102649	1980234
1984	0	101925	51206	2352	392957	8912	0	0	99884	32425	7182	11145	0	4869	1752	714607
1985	0	15823	210029	138498	74321	50087	1701	0	24792	0	3359	204441	4499	95233	0	822783
1986	304	311914	5759	14197	147742	283409	37417	0	7339	0	37646	70265	1248	5559	5037	927836
1987	10067	413639	32158	4970	361026	47036	2179	0	112191	2375	29806	608	2586	21023	2486	1042151
1988	1868	62277	12186	248687	809402	31979	1632	0	99410	12427	3726	1460	0	4397	15493	1304943
1989	1490	263712	754493	2056356	2762381	25588	0	0	829875	2725	48283	327784	2286	7427	458072	7540472
1990	0	119177	13234	38891	263705	40627	7179	0	136340	1330	97971	95336	7809	3745	69345	894688
1991	2750	17909	387439	68554	393094	417959	3477	277	66844	12830	7786	113914	0	11114	52268	1556215
1992	0	2050	188145	6783	405849	36629	4803	0	28881	400	6608	50359	353	5424	89588	825872
1993	850	848930	98804	48620	459811	105429	304	0	358140	0	25741	23233	0	0	801	1970664
1994	1555	1633382	2915469	212146	823095	9471	0	0	15560	0	81585	380042	592	11358	38535	6122790
1995	0	3001420	9641	199321	1999246	289053	26475	0	1202198	0	0	300711	1003	2632	255250	7286949
1996	0	204638	248758	313536	477511	381922	1315	0	14775	0	9942	58652	0	435	98917	1810402
1997	0	13200	60690	72332	9834	345966	0	0	1321	2766	0	10714	0	3126	14556	534504
Total	72397	14293356	9420121	4308271	19912508	5248249	161518	7361	9469459	253574	929557	4213088	78804	938924	1576071	70883261
AAB	1856	366496	241542	110468	510577	134570	4141	189	242807	6502	23835	108028	2021	24075	40412	1817520
PAAB	0.057%	0.702%	0.763%	0.241%	0.761%	0.145%	0.023%	0.006%	0.418%	0.047%	0.202%	0.392%	0.013%	0.058%	0.123%	

21562024, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

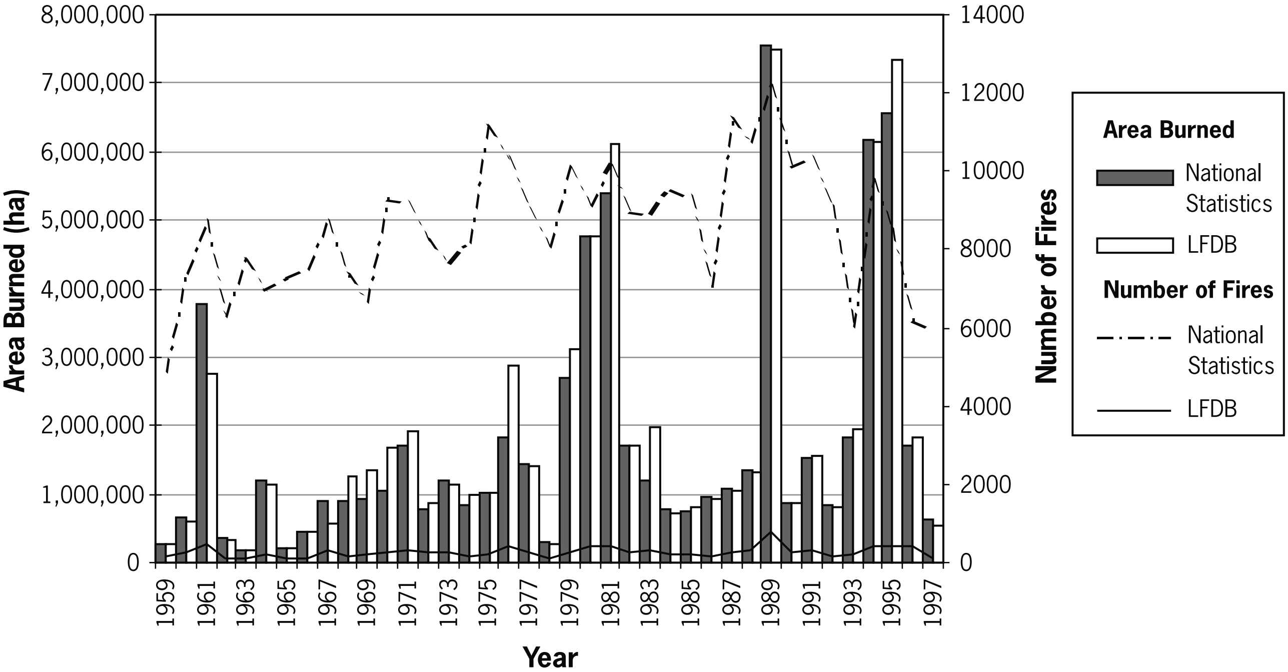

Figure 2. LFDB (fires >200 ha) and official (all fires) annual fire numbers and area burned for Canada 1959–1997.

Ontario, Manitoba, Saskatchewan, and the Northwest Territories) that occurred between 1959 and the mid-1970s are undoubtedly missing from this analysis. National air photography archives are being used in an attempt to improve this situation. Finally, fire reports for the 1970s in Saskatchewan have been lost after digitizing, and the only record available is for the polygons of fires >1000 ha. Attributes for these fires, other than location, year and size, are spotty within and between years.

[10] Fire data were analyzed by Canadian ecozones or ecoregions, rather than provinces/territories, using the classification system developed by the *Ecological Stratification Working Group* [1995]. Ecozones are shown in Figure 1. Only forest fire data are included in this analysis. Agricultural and rangeland fires are not well-documented and have been excluded. Ecozone/ecoregion level analysis incorporates climate and vegetation to some degree, better reflecting the continuity of the landscape, but does not take provincial fire management policies into consideration. For this analysis, the Taiga Shield and Boreal Shield Ecozones have been separated into west and east components, based on climate and fire activity disparities.

2.2. Data Analysis

[11] For the 1959–1997 period the LFDB contains attribute data for a total of 10,448 Canadian fires. A very small percentage of LFDB fires have some missing attributes, so the numbers used in each of the following analyses vary slightly.

[12] The Annual Area Burned (AAB) calculated for individual ecozones and ecoregions was determined by totalling the area burned within an ecozone over the 1959–1997 period and dividing by 39. This number was then divided again by the forested area within each ecozone and multiplied by 100 to determine the Percent Annual Area Burned (PAAB). Forested areas (which exclude lakes and large non-fuel areas) were derived from the National Forest Inventory Database of the Canadian Forest Service.

[13] Fire causes were listed for almost all fires except for missing Saskatchewan data for 1972–1975, which were considered lightning-caused. For this analysis the small number of fires in other provinces/territories listed with an "unknown" cause were assumed to be human-caused.

[14] The ignition date was available for all LFDB fires and was used to investigate the seasonal trends in national fire activity. Both fire numbers and area burned were compiled by 10 or 11 day periods for all lightning- and human-caused fires.

[15] Not all fires are actioned (i.e., suppression attempted) in Canada. Most fires are identified if they received some suppression action, although the level of suppression is highly variable. For this analysis of actioned and non-actioned fires all LFDB fires in British Columbia and Alberta were considered actioned, based on policies that existed in these provinces during the study period, while 1970–1979 Saskatchewan fires were considered non-actioned.

3. Results and Discussion

3.1. Number of Fires and Area Burned

[16] The annual area burned by Canadian ecozones for the 1959–1997 period is summarized in Table 1. Clearly, the largest areas burned occur in the boreal/taiga shield and plains regions of Canada, particularly in the large Taiga Plains, Taiga Shield West/East, Boreal Shield West/East and Boreal Plains ecozones, which account for 88% of the total area burned over the 39-year period. These ecozones contain large areas where values-at-risk generally do not warrant aggressive fire suppression, and the majority of

21562202d, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

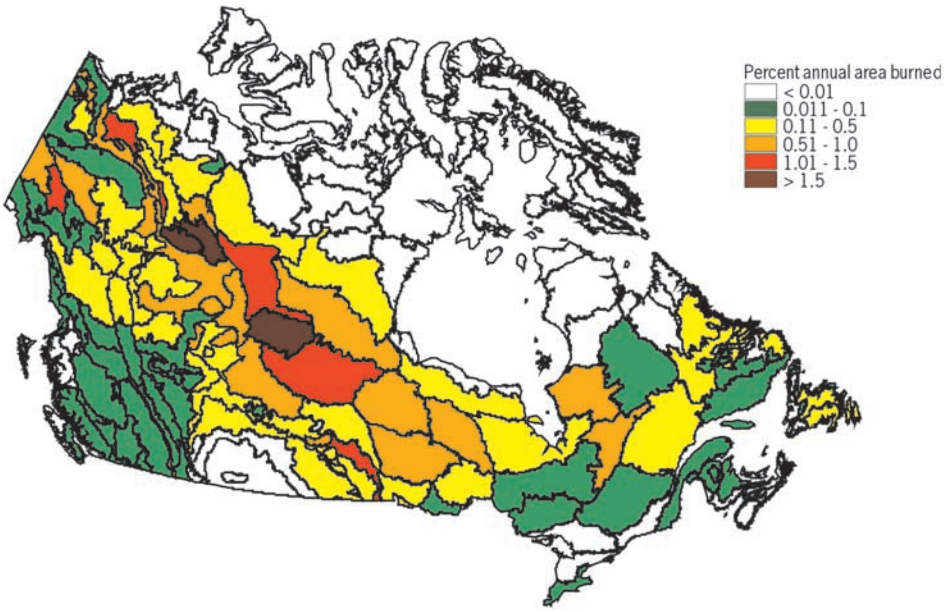

Figure 3. LFDB percent annual area burned (PAAB) distribution across Canada for 1959–1997 period by ecoregions.

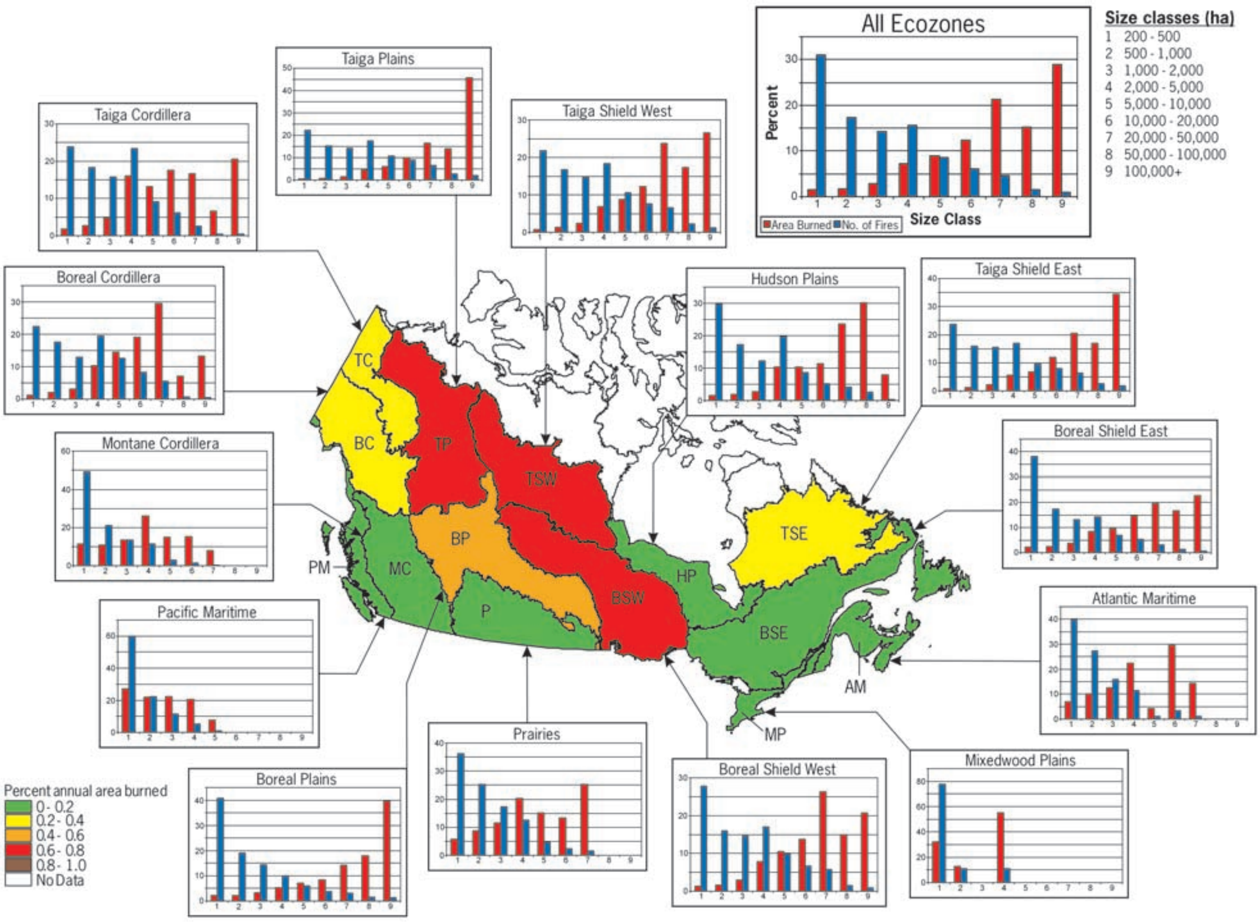

Figure 4. LFDB percent annual area burned (PAAB), and fire occurrence and area burned by fire size classes for Canadian ecozones.

21562024, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Table 2. Mean LFDB Annual Area Burned (ha) by Fire Size Classes and Ecozones[a]

Size Class	1	2	3	4	5	6	7	8	9	Total
SA	27	166	276	278	208	0	901	0	0	1856
TP	2122	3182	5909	16091	22383	36688	60706	51379	168036	366496
TSW	1879	3235	5810	16601	21298	29692	57262	41682	64081	241542
TSE	876	1255	2364	6186	7473	13147	22560	18611	37996	110468
BSW	6606	8439	15430	39632	53508	70240	134644	76267	105812	510577
BSE	3101	3180	4981	11281	12851	19791	26415	22372	30599	134570
AM	284	421	522	923	178	1221	594	0	0	4141
MP	61	24	0	104	0	0	0	0	0	189
BP	5264	5210	7852	12656	17073	20259	34614	43561	96318	242807
P	377	575	744	1314	983	868	1640	0	0	6502
TC	413	658	1129	3841	3159	4199	3965	1582	4888	23835
BC	1301	2201	3273	11237	15563	20718	31828	7560	14347	108028
PM	550	446	451	418	156	0	0	0	0	2021
MC	2729	2601	3290	6282	3625	3659	1889	0	0	24075
HP	618	761	1125	4196	4207	4573	9562	12164	3205	40412
National	26206	32354	53158	131041	162665	225054	386580	275178	525283	1817520

[a]1997–1959 = 39 years. Size classes (ha) are as follows: 1, 200 – 500; 2, 500 – 1,000; 3, 1,000 – 2,000; 4, 2,000 – 5,000; 5, 5,000 – 10,000; 6, 10,000 – 20,000; 7, 20,000 – 50,000; 8, 50,000 – 100,000; and 9, 100,000+.

fires are allowed to burn naturally. This, coupled with the more continental climate and generally more extreme fire danger conditions in these regions of Canada largely explains the greater areas burned in these ecozones. High area burned rates are also evident in the Taiga and Boreal Cordillera ecozones, while all other ecozones exhibit significantly less large fire activity, primarily due to intensive levels of fire protection and/or generally less severe fire weather and fuel conditions.

[17] The distribution of all LFDB fires for the 1959–1997 period, along with ecozone boundaries, is shown in Figure 1. Once again the concentration of large fire activity in the Boreal and Taiga Ecozones is quite evident, as is the northwest/southeast distribution of fires across the Canadian boreal zone. Relatively low fire activity is also observed in southern Canada, particularly in south/central Ontario, the Maritime provinces, and coastal British Columbia. Very few fires occur in the tundra and mountainous regions of northern Canada due to a lack of fuel continuity. Note that the values in Table 1 are slightly different than those reported by *Amiro et al.* [2001a] due to some recent updates in the LFDB.

[18] The number of fires and area burned for both the official Canadian statistics and the LFDB are shown in Figure 2 for the 1959–1997 period. One would expect the annual LFDB area burned totals to be somewhat less than the published official record, as only fires >200 ha are represented in this database. However, in many years, most noticeably during the late 1960s, the 1970s, and the early 1980s, the area burned in the LFDB exceeds that in the official statistics. This is primarily due to the fact that large fires burning outside the intensive protection zone in Quebec were not included in national statistical summaries during this period. The Quebec Ministry of Natural Resources is currently reviewing fire reports and digitizing fire maps for many of these previously unreported fires, and they have been added to the LFDB. In addition, the larger area burned figures in the LFDB for 1995 are the result of more recent and accurate data reporting from Saskatchewan.

[19] During the 1959–1997 period official Canadian statistics [e.g., *Higgins and Ramsey*, 1992; *Canadian Council of Forest Ministers*, 1997] report a total of 332,467 fires burning over an area of 68,369, 752 ha. The LFDB numbers for this period are 10,448 fires (i.e. ~3.1% of the total number) and a total area burned of 71,016,759 ha. A total of 77 fires (totalling 133,498 ha) in the LFDB lacked a location, so were not used in the ecozone analyses in this paper. Given the revised statistics from Quebec, the LFDB numbers represent the best estimate of area burned in Canada post-1959, although it is recognized that fires <200 ha are not included, and that northern fires across much of west-central Canada are likely under-reported prior to the early 1970s.

3.2. Fire Frequency

[20] The frequency of large fires within an ecozone is often represented by determining the percent annual area burned (PAAB), which takes ecozone size into account. Based on the area burned annually in each ecozone over the 39 years of record, and the actual forested area within that ecozone, a PAAB can be determined. These are given at the bottom of Table 1. As expected, PAAB figures are highest, and almost identical, in the Taiga Shield West and Boreal Shield West ecozones, and almost as high for the Taiga Plains ecozone. In these combined areas an average of ~0.74% of the land area burns annually. Fire affects significant portions of the Taiga Shield East, Boreal Shield East, Boreal Plains, and Boreal Cordillera ecozones as well, but is not a major factor, in terms of area burned, in the remaining Canadian ecozones.

[21] Just as area burned varies dramatically between ecozones, it is also highly variable within ecozones. A higher resolution picture of large fire activity across Canada emerges in Figure 3, where the PAAB for the 1959–1997 period is presented for ecoregions within ecozones. At this scale greater variability in PAAB is evident, with nine ecoregions showing PAAB levels above 1%. It is recognized that the relatively short period of analysis (39 years) in this study can result in large fires in smaller ecoregions disproportionally affecting the results. This reinforces the need to extend the LFDB as far back in time as possible.

3.3. Fire Size

[22] LFDB statistics were aggregated by fire size classes to produce the distributions of fire frequency and area burned by ecozones in Figure 4. Actual mean annual area

21562202d, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

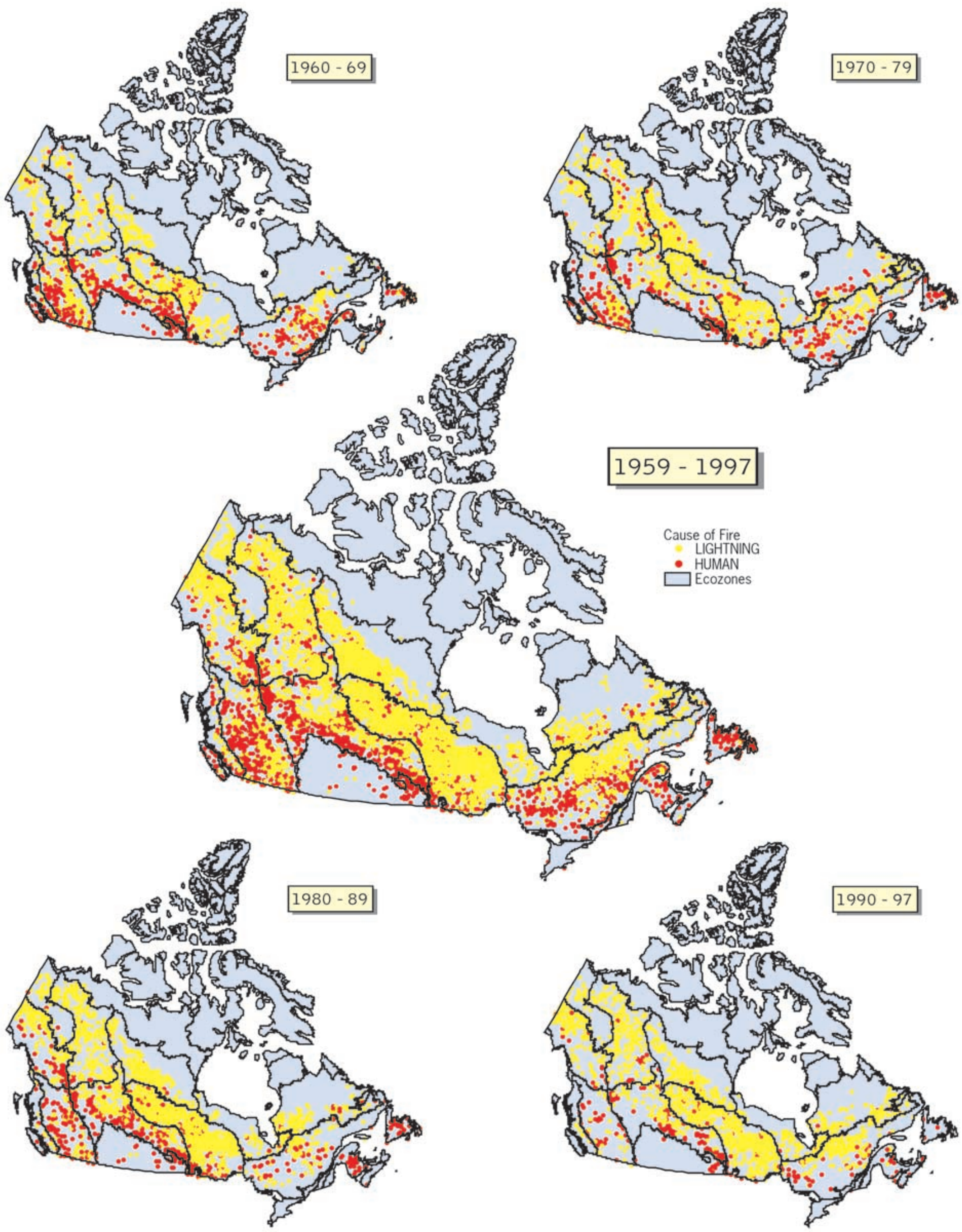

Figure 5. LFDB lightning and human-caused fire distribution by decades.

21562202d, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

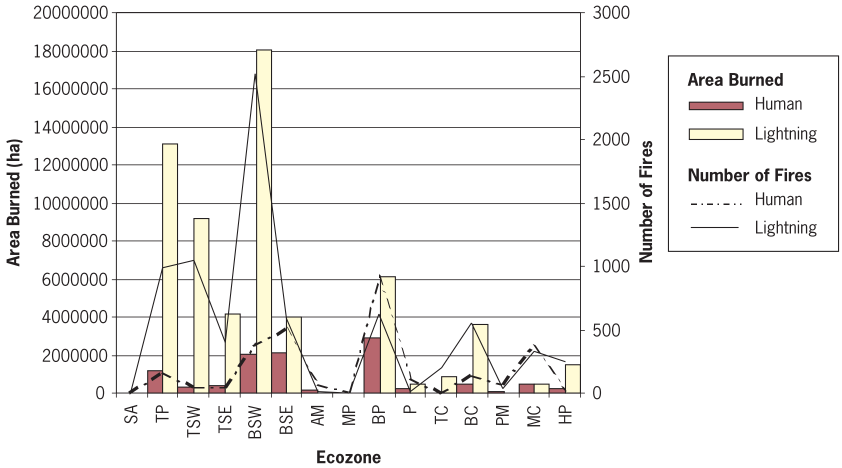

Figure 6. LFDB lightning and human-caused fire numbers and area burned by ecozones 1959–1997 (ecozone code names given in legend of Figure 1).

burned numbers by size class and ecozone are listed in Table 2. Generally speaking, the number of fires decreases with increasing size class while the contribution to overall area burned increases, with a relatively small number of larger fires influencing area burned significantly. This is true at a national level, and particularly in all boreal and taiga ecozones with a high degree of large fire activity. For example, at a national scale 31% of LFDB fires fall in the 200–500 ha size class yet account for only 1.4% of the area burned, while the 2.5% of fires exceeding 50,000 ha represent 44% of the area burned. Some ecozones in southern Canada experience large fires infrequently or not at all, primarily due to more intensive protection and less severe fire weather.

3.4. Fire Cause

[23] The geographical distribution of lightning- and human-caused fires across Canada by decades is illustrated in Figure 5. Lightning fires predominate in all decades, and account for virtually all large fires in northern ecozones. Human-caused fires tend to occur, as expected, in the more populated and southerly regions of the country. The absence of large fires in some northern regions in the 1960s, particularly northwestern Ontario and northern Quebec/Labrador, regions that exhibit high levels of fire activity in subsequent decades, is almost certainly a reflection of a lack of complete fire monitoring at that time. In the 1960s significant fire activity is evident in southern Quebec with very few large fires to the north. However, this trend was reversed by the 1980s and has been maintained since. In addition, prior to the advent of lightning detection systems in the 1970s it is likely that some lightning-caused fires were misidentified as fires caused by humans. A more detailed analysis of the baseline data used to construct Figure 5 shows that over the 1959–1997 period ~72% of all LFDB fires were caused by lightning, with these fires accounting for ~85% of the total area burned. Decadal trends show the increasing contribution of lightning fires to national area burned over time, with the percentage of lightning fires in the LFDB rising - 53% in the 1960s, 71% in the 1970s, 78% in the 1980s to 86% in the 1990s. At the same time the relative area burned by lightning increased as well - 55% in the 1960s, 87% in the 1970s, 88% in the 1980s to 94% in the 1990s. This steady proportional increase is likely due to an expanded fire detection and monitoring capability in northern regions of Canada since the mid-1970s, along with improved management of human-caused fires through prevention and aggressive initial attack.

[24] The total number of lightning- and human-caused fires and area burned by ecozones for the 1959–1997 period are shown in Figure 6. This supports the visual representation in Figure 5 that lightning fires predominate in northern Canada.

3.5. Seasonality

[25] The Canadian forest fire season generally begins in April in the southern regions of the country, and continues through mid-October, although the season can be longer in British Columbia and parts of Alberta. The temporal distribution of fire occurrence and area burned throughout the fire season, by 10–11 day increments, is illustrated in Figure 7 for the 1959–1997 period. Human-caused fire activity dominates fire numbers during the April–May period, and during the fall, with lightning fire numbers taking over during the late spring and summer period. As expected the seasonal trend in area burned is dominated by lightning fires during the summer months. This is entirely consistent with the development of the Canadian fire season, with fire activity beginning later in the season with movement northward, and supports *Harrington* [1982] who found May as the most active fire month in Alberta, while the rest of the country below 60°N latitude reported most fire activity in June, with the Northwest Territories experiencing peak fire activity in July.

3.6. Degree of Suppression Action on Fires

[26] Not all Canadian fires receive suppression action. The LFDB contains some attribute information on whether a given fire was actioned, but the level of action is highly variable, ranging from limited protection of a few remote cabins to deployment of major resources during a large campaign fire where there are many values at risk. In addition, the LFDB only includes fires greater than 200 ha

21562024, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

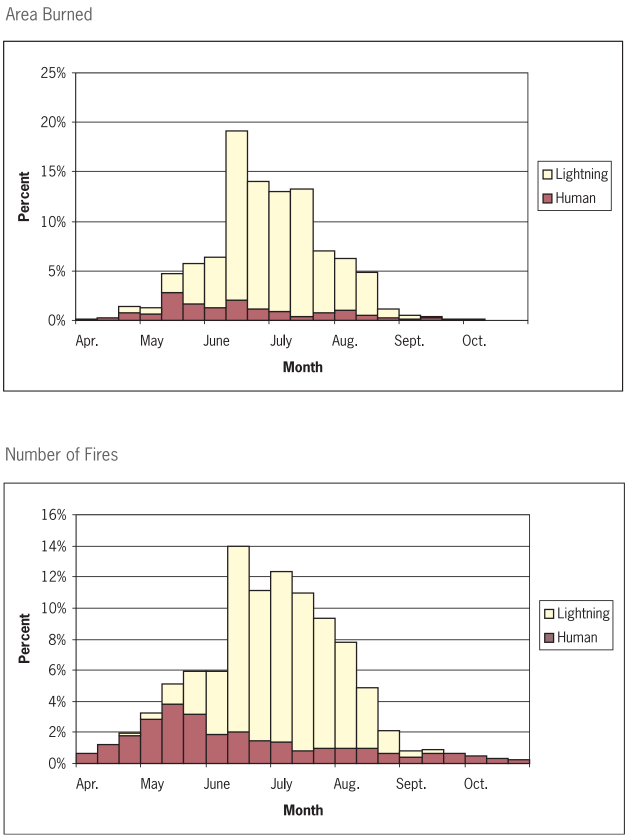

Figure 7. LFDB human-caused and lightning fire numbers and area burned (%) throughout the April–October period.

in final size, so smaller fires that may have grown in the absence of effective suppression are not included. Therefore, a division of LFDB fires between those actioned and non-actioned cannot be used as a measure of suppression effectiveness. However, the categories do show the spatial distribution of actions on Canadian fires (Figure 8). Most of the non-actioned fires are in remote areas where access is poor, timber harvesting is limited, and communities are sparse. They are mostly caused by lightning in the northern part of the country (compare Figure 8 and Figure 5). Except for protection of communities, some Canadian fire management agencies have zones delineated for fire actions (e.g. intensive and extensive protection zones), and these can be generally seen in Figure 8 by the division between the two action classes. In some areas, these zones have changed over time. The action category had not been identified for about 12% of the burned area in the LFDB and these fires have been classified based on their location in certain fire zones, or whether a certain agency has a uniform policy for suppression activities. For the 1959–97 period, ~50% of the area burned, or an annual average of ~860,000 ha, was by non-actioned fires. Non-actioned fires that occur in a region zoned for no suppression (except for protecting a specific value such as a community) reflect a natural fire regime. Given the previously stated caveats, the picture that emerges illustrates the geographical impact of fire management and other land use and management changes in general in Canada. Suppression action is generally taken more often on fires in the lower boreal zone, while values-at-risk generally dictates that more northerly fires often receive little or no suppression, and fire is allowed to assume its natural role.

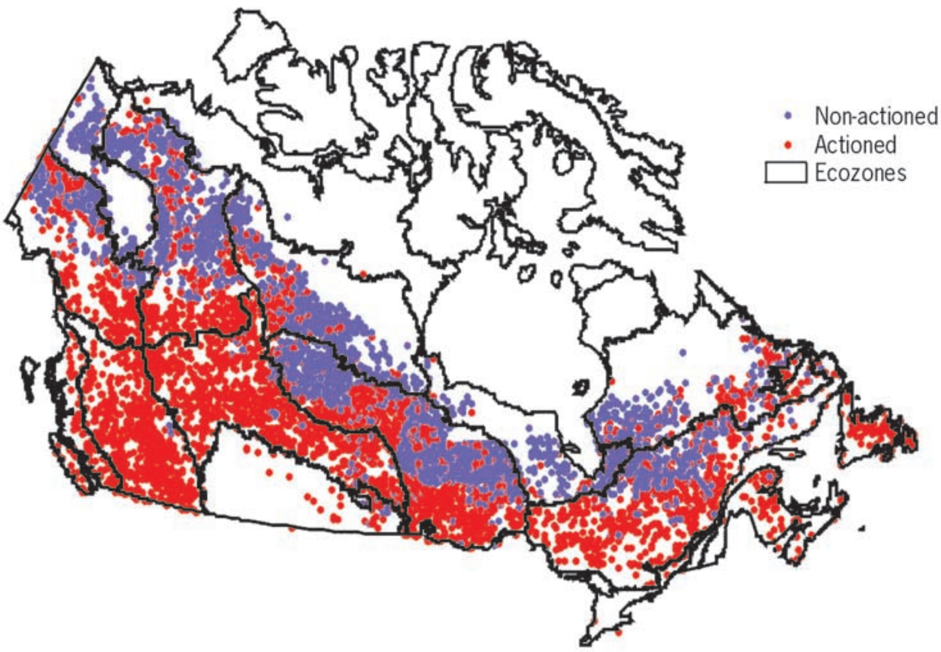

Figure 8. Geographical distribution of LFDB actioned and non-actioned fires across Canada for the 1959–1997 period.

21562202d, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

4. Conclusions

[27] A LFDB of forest fires larger than 200 ha in area has been developed for Canada. The present LFDB is reasonably complete for the 1959 to 1997 period, and is being extended to include more recent data as they become available. In addition, pre-1959 data are being compiled for most of the country, although there are some missing regions and the older statistics are less certain. This database contains only a small fraction of the fires that occur in Canada, so should not be interpreted as a reflection of the Canadian approach to fire management. This approach results in the suppression of ~97% of Canadian fires in the interest of protecting human life, property and forest resources. However, the economics and ecology of fire suppression dictate that natural fire should play a major role in boreal ecosystems, and the Canadian fire management approach accommodates this need. Nevertheless, the LFDB described here permits the description of recent Canadian fire regimes. On average, about 1.8 million ha burned annually in these large fires, but more than 7 million ha burned in some years. It is likely that only an additional few percent of the area burned was the result of fires less than 200 ha in size, even though small fires are more than an order of magnitude more numerous than large fires. The fires mostly occurred in the boreal and taiga regions, where about 0.7% of the forested area burned annually as an ecozone average. Some individual ecoregions have experienced 2.9% of the forest area burned annually during this period. More than 70% of LFDB fires were caused by lightning, but burned about 85% of the area, mostly in the north where population is sparse. The median fire size was 1040 ha, but the mean was 6797 ha, because a few of the very large fires contributed greatly to the total area burned, although this distribution varied among ecozones. At the national scale, the main fire season was from late April to the end of August with most of the area burned occurring in June and July. Almost half of the area burned was by fires that were not actioned (i.e., suppressed to some degree), mostly in remote areas not being protected from fire except where communities were threatened. The LFDB data have been used to estimate direct carbon emissions from fires [*Amiro et al.*, 2001a], are a baseline for studies of climate change impacts on fire [*Amiro et al.*, 2001b; *Flannigan et al.*, 1998; *Flannigan et al.*, 2000; *Stocks et al.*, 1998], and are part of the overall effort in modeling the carbon balance for the Canadian forest sector [*Kurz and Apps*, 1999].

[28] **Acknowledgments.** Development of the Canadian LFDB is an ongoing enterprise which has required the efforts of many organizations and individuals over the past 12 years. The authors thank all Canadian provincial, territorial, and federal agencies, and their staffs for the provision of fire records, and their continuing assistance in compiling these data. We also thank K. Power for the provision of forest inventory data for Canadian ecoregions, and B.S. Lee and Hua Sun for early contributions to the development of the LFDB. This study was partly funded by the Climate Change Action Fund (CCAF), and the Energy from FORest Biomass (ENFOR) Program of the Canadian government.

References

Amiro, B. D., J. B. Todd, B. M. Wotton, K. A. Logan, M. D. Flannigan, B. J. Stocks, J. A. Mason, D. L. Martell, and K. G. Hirsch, Direct carbon emissions from Canadian forest fires, 1959 to 1999, *Can. J. For. Res*, *31*, 512–525, 2001a.

Amiro, B. D., B. J. Stocks, M. E. Alexander, M. D. Flannigan, and B. M. Wotton, Fire, climate change, carbon and fuel management in the Canadian boreal forest, *Int. J. Wildland Fire*, *10*, 405–413, 2001b.

Cahoon, D. R., B. J. Stocks, L. S. Levine, W. R. Cofer, and J. M. Pierson, Satellite analysis of the severe 1987 forest fires in northern China and southeastern Siberia, *J. Geophys. Res.*, *99*, 18,627–18,638, 1994.

Cahoon, D. R., B. J. Stocks, J. S. Levine, W. R. Cofer, and J. A. Barber, Monitoring 1992 forest fires in the boreal ecosystem using NOAA AVHRR satellite imagery, in *Biomass Burning and Global Change*, edited by J. S. Levine, pp. 848–873, MIT Press, Cambridge, Mass., 1996.

Canadian Council of Forest Ministers, *Compendium of Canadian Forestry Statistics 1996*, Nat. Resour. Can., Ottawa, 1997.

Ecological Stratification Working Group, A national ecological framework for Canada, Agric. and Agri-Food Can. and Environ. Can., Ottawa, 1995.

Flannigan, M. D., and J. B. Harrington, A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953–80), *J. Appl. Meteorol.*, *27*, 441–452, 1988.

Flannigan, M. D., Y. Bergeron, O. Engelmark, and B. M. Wotton, Future wildfire in circumboreal forests in relation to global warming, *J. Veg. Sci.*, *9*, 469–476, 1998.

Flannigan, M. D., B. J. Stocks, and B. M. Wotton, Climate change and forest fires, *Sci. Tot. Environ.*, *262*, 221–229, 2000.

Harrington, J. B., A statistical study of area burned by wildfire in Canada 1953–1980, *Inf. Rep. PI-X-16*, Can. For. Serv., Petawawa Natl. For. Inst., Chalk River, Ontario, Can., 1982.

Harrington, J. B., M. D. Flannigan, and C. F. Van Wagner, A study of the relation of components of the Fire Weather Index System to monthly provincial area burned by wildfire in Canada 1953–80, *Inf. Rep. PI-X-25*, Can. For. Serv., Petawawa Natl. For. Inst., Chalk River, Ontraio, Can., 1983.

Higgins, D. G., and G. S. Ramsey, Canadian forest fire statistics: 1988–1990, For. Can. Inf. Rep. PI-X-107, Petawawa Natl. For. Inst., Chalk River, ON, 76 pp, 1992.

Johnson, E. A., Fire and vegetation dynamics: Studies from the North American boreal forest, Cambridge Univ. Press, New York, 1992.

Kasischke, E. S., Boreal ecosystems and the global carbon cycle, in *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, *Ecol. Stud.*, vol. 138, edited by E. S. Kasischke and B. J. Stocks, pp. 19–30, Springer-Verlag, New York, 2000.

Kasischke, E. S., and B. J. Stocks (Eds.), *Fire, Climate Change, and Carbon Cycling in the Boreal Forest, Ecological Studies*, vol. 138, 461 pp., Springer-Verlag, New York, 2000.

Kasischke, E. S., K. Bergen, R. Fennimore, F. Sotelo, G. Stephens, A. Janetos, and H. Shugart, Satellite imagery gives a clear picture of Russia's boreal forest fires, *Eos Trans. AGU*, *80*, 141–147, 1999.

Kurz, W. A., and M. J. Apps, A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector, *Ecol. Appl.*, *9*, 526–547, 1999.

Levine, J. S., (Ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, MIT Press, Cambridge, Mass., 1991.

Levine, J. S. (Ed.), *Biomass Burning and Global Change*, MIT Press, Cambridge, Mass., 1996.

Malanson, G. P., Diversity, stability, and resilience: effects of fire regime, in *The Role of Fire in Ecological Systems*, edited by L. Trabaud, pp. 49–63, SPB Acad., Hague, 1987.

Murphy, P. J., J. P. Mudd, B. J. Stocks, E. S. Kasischke, D. Barry, M. E. Alexander, and N. F. H. French, Historical fire records in the North American boreal forest, in *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, *Ecol. Stud.*, vol. 138, edited by E. S. Kasischke and B. J. Stocks, pp. 274–288, Springer-Verlag, New York, 2000.

Price, C., and D. Rind, The impact of a 2 × CO_2 climate on lightning-caused fires, *J. Clim.*, *7*, 1484–1494, 1994.

Stocks, B. J., The extent and impact of forest fires in northern circumpolar countries, in *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, edited by J. S. Levine, pp. 197–202, MIT Press, Cambridge, Mass., 1991.

Stocks, B. J., and A. J. Simard, Forest fire management in Canada, *J. Disaster Mgt.*, *5*, 21–27, 1993.

Stocks, B. J., D. R. Cahoon, W. R. Cofer, and J. S. Levine, Monitoring large-scale forest fire behavior in northeastern Siberia using NOAA-AVHRR satellite imagery, in Biomass Burning and Global Change, edited by J. S. Levine, pp. 802–807, MIT Press, Cambridge, MA, 1996a.

Stocks, B. J., B. S. Lee, and D. L. Martell, Some potential carbon budget implications of fire management in the boreal forest, in Forest Ecosystems, Forest Management and the Global Carbon Cycle, *NATO ASI Ser. 1*, Vol. 40, edited by M. J. Apps and D. T. Price, pp. 89–96, Springer-Verlag, New York, 1996b.

Stocks, B. J., et al., Climate change and forest fire potential in Russian and Canadian boreal forests, *Clim. Change*, *38*, 1–13, 1998.

Stocks, B. J., B. M. Wotton, M. D. Flannigan, M. A. Fosberg, D. R. Cahoon, and J. G. Goldammer, Boreal forest fire regimes and climate change, in *Remote Sensing and Climate Modelling: Synergies and Lim-*

21562024, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

itations, edited by M. Beniston and M. M. Verstraete, pp. 233–246, Kluwer Acad., Norwell, Mass., 2001.

Swetnam, T. W., Fire history and climate change in giant sequoia groves, *Science*, *262*, 885–889, 1993.

Van Wagner, C. E., The development and structure of the Canadian Forest Fire Weather Index System, *Tech. Rep. 35*, Can For Serv, Ottawa, Ont., Can., 1987.

Van Wagner, C. E., The historical pattern of annual burned area in Canada, *For. Chron.*, *64*, 182–185, 1988.

Weber, M. G., and M. D. Flannigan, Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes, *Environ. Rev.*, *5*, 145–166, 1997.

Weber, M. G., and B. J. Stocks, Forest fires and sustainability in the boreal forests of Canada, *Ambio*, *27*, 545–550, 1998.

Whelan, R. J., *The Ecology of Fire*, 346 pp., Cambridge Univ. Press, New York, 1995.

Wotton, B. M., and M. D. Flannigan, Length of the fire season in changing climate, *For. Chron.*, *69*, 187–192, 1993.

B. D. Amiro, M. D. Flannigan, K. G. Hirsch, and J. B. Todd, Canadian Forest Service, Northern Forestry Centre, 5320-122 Street, Edmonton, AB, T6H 3S5, Canada.

E. M. Bosch, K. A. Logan, J. A. Mason, B. J. Stocks, and B. M. Wotton, Canadian Forest Service, Great Lakes Forestry Centre, 1219 Queen Street East, Sault Ste. Marie, ON, P6A 2E5, Canada. (bstocks@nrcan.gc.ca)

D. L. Martell, Faculty of Forestry, University of Toronto, 33 Willcocks Street, Toronto, ON, M5S 3B3, Canada.

W. R. Skinner, Meteorological Service of Canada, 4905 Dufferin Street, Downsview, ON, M3H 5T4, Canada.

21562202d, 2002, D1, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2001JD000484 by Zentralbibliothek Zürich, Wiley Online Library on [21/11/2022]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License