Direct carbon emissions from Canadian forest fires, 1959–1999

B.D. Amiro, 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

Abstract: Direct emissions of carbon from Canadian forest fires were estimated for all Canada and for each ecozone for the period 1959–1999. The estimates were based on a data base of large fires for the country and calculations of fuel consumption for each fire using the Canadian Forest Fire Behaviour Prediction System. This technique used the fire locations and start dates to estimate prevailing fire weather and fuel type for each of about 11 000 fires. An average of 2×10^6 ha·year^{-1} was burned in this period, varying from 0.3×10^6 ha in 1978 to 7.5×10^6 ha in 1989. Ecozones of the boreal and taiga areas experienced the greatest area burned, releasing most of the carbon (C). The mean area-weighted fuel consumption for all fires was 2.6 kg dry fuel·m^{-2} (1.3 kg C·m^{-2}), but ecozones vary from 1.8 to 3.9 kg dry fuel·m^{-2}. The mean annual estimate of direct carbon emissions was 27 ± 6 Tg C·year^{-1}. Individual years ranged from 3 to 115 Tg C·year^{-1}. These direct fire emissions represent about 18% of the current carbon dioxide emissions from the Canadian energy sector, on average, but vary from 2 to 75% among years. Post-fire effects cause an additional loss of carbon and changes to the forest sink condition.

Résumé : Les émissions directes de carbone provenant des feux dans les forêts canadiennes ont été estimées pour l'ensemble du Canada et pour chacune des écozones pendant la période de 1959 à 1999. Les estimés s'appuient sur une base de données sur les feux importants survenus au pays et sur des calculs de consommation de combustibles pour chaque feu à l'aide du Système canadien de prédiction du comportement des feux de forêt. Cette technique utilise la localisation et la date de début des feux pour estimer les conditions météorologiques qui prévalaient au moment du feu et le type de combustibles pour chacun des quelques 11 000 feux. Pendant cette période, 2×10^6 ha par année en moyenne ont brûlé, allant de $0,3 \times 10^6$ ha en 1978 à $7,5 \times 10^6$ ha en 1989. Les plus grandes superficies brûlées se retrouvent dans les écozones de la région boréale et de la taïga et sont responsables de la majeure partie des émissions de carbone (C). La consommation moyenne de combustibles, pondérée par la surface pour l'ensemble des feux, est de 2,6 kg de combustible anhydre par m^2 (1,3 kg de carbone par m^2) mais la quantité varie de 1,8 à 3,9 kg de combustible anhydre par m^2 selon les écozones. L'estimé annuel moyen des émissions directes de carbone est de 27 ± 6 Tg C·an^{-1}. Selon les années, la quantité varie de 3 à 115 Tg C·an^{-1}. Ces émissions directes causées par le feu représentent en moyenne environ 18% des émissions actuelles de dioxyde de carbone en provenance du secteur énergétique canadien mais varient de 2 à 75% selon les années. Les effets indirects du feu causent une perte additionnelle de carbone et altèrent la situation des forêts en tant que puits de carbone.

[Traduit par la Rédaction]

1. Introduction

Carbon sequestration by forests is an important part of the earth's overall carbon balance (Dixon et al. 1994). The boreal forest especially may influence global carbon balances because of its large areal extent with strong fluxes during the growing season (D'Arrigo et al. 1987; Bonan 1991). The potential forest sink is recognized in the Kyoto Protocol, and includes activities of afforestation, reforestation, and deforestation (IGBPTCWG 1998). The view of boreal forests as a static carbon sink has largely been replaced by dynamic models of an evolving forest that is continually being renewed by disturbance. For example, Kurz and Apps (1999) suggest that the Canadian boreal forest has likely become a recent carbon source because of the impact of insects and fire through the 1970s and 1980s.

Fire is recognised as driving much of the boreal forest carbon balance in North America and Siberia (Dixon and Krankina 1993; Kasischke et al. 1995; Stocks et al. 1996; Conard and Ivanova 1997; Kasischke and Stocks 2000). Fires release most carbon as CO_2, but quantities of CO, CH_4, nitrogen oxides, particulate matter, and other trace gases are also released (Hegg et al. 1990; Radke et al. 1991; Cofer et al. 1998). Hence, fires not only impact carbon sequestration by forests, but emit greenhouse gases that potentially affect the climate. This has some potential positive feedback since greenhouse-gas-driven climate warming may increase fire activity (Flannigan et al. 1998), which increases greenhouse gases. In addition, burned areas change the surface energy

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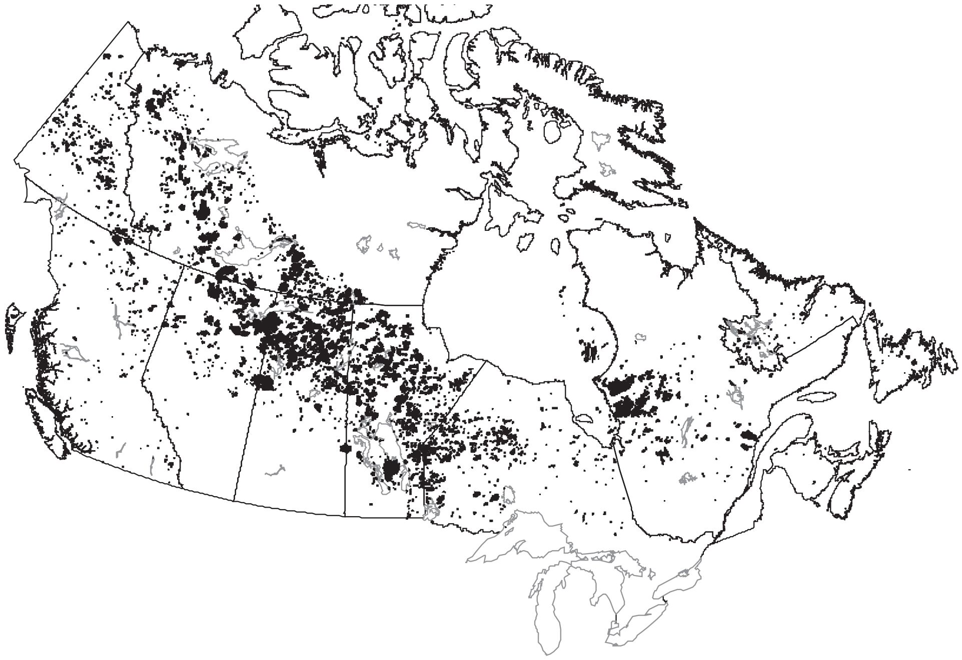
Fig. 1. Map of large fires in Canada, 1980–1994. Each solid polygon shows an area burned.



balance (Rouse 1976; Amiro et al. 1999; Amiro 2001) and this may affect local and regional climates.

Canadian fire records from 1930 to present indicate that about 1.3 × 10^6 ha of forest is burned annually on average, with extreme fire years burning more than 7 × 10^6 ha (Weber and Stocks 1998). We believe that the area burned before about 1960 was underestimated because of incomplete statistics, and the mean since then is 2 × 10^6 ha, with a trend to increased fire in the 1980s and 1990s. Provincial, territorial, and federal agencies maintain data on fires in each of their jurisdictions, and these data sets have been recently combined into the Canadian Large-Fire Data Base (LFDB). All fires greater than or equal to 200 ha in area in designated forest areas (i.e., rangelands are excluded) are explicitly mapped in a geographical information system (GIS). These larger fires are most important, since they represent typically about 2–3% of the total fires but account for 97–98% of the area burned (Stocks 1991). This data base includes attribute information on the point of ignition, fire start date, area burned, suppression actions, and cause of ignition. This data base is still being improved, and at present we have reasonable confidence in the fire record data for the 1959–1995 period. Fire polygon data are also available for 1980 to 1994, which dramatically illustrates the impact of fire on the landscape (Fig. 1).

Direct carbon emissions are calculated as the product of fuel combusted during the fire (Stocks and Kauffman 1997) and area burned. In the present study, we use the LFDB and the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada 1992) to estimate carbon emissions from fire for the 1959–1999 period.

2. Methods

2.1. Ecozones and ecoregions

Carbon emissions were calculated for each ecoregion, following the Canadian ecoregion classification of the Ecological Stratification Working Group (1996). The ecoregion level was selected since it represents distinctive regional ecological factors, such as climate and vegetation, and is usually much larger than an individual fire. It transcends provincial boundaries, which reflects the continuity of the landscape, but neglects differences in provincial fire suppression policies. The use of ecoregions is central to our classification of fuel types (see Section 2.4). Ecoregions cover scales ranging from 2000 to 22 × 10^6 ha in area.

Fires occurred in over 130 ecoregions during the analysis period. Although this unit was appropriate for the analysis, it is too small to present the summary data. Hence, we grouped the ecoregion data into ecozones (Ecological Stratification Working Group 1996). Fires occurred in 14 of the 15 Canadian ecozones (Fig. 2). However, the Boreal Shield and Taiga Shield ecozones transcend the east-west moisture gradient across the country, and we see some obvious differences in fire occurrence across this area (Fig. 1). Therefore, we split the Taiga Shield ecozone into Taiga Shield West and Taiga Shield East using Hudson Bay as the divider. We also split the Boreal Shield ecozone at the north tip of Lake Superior where the Boreal Shield West ecozone includes ecoregion numbers less than or equal to 95 and Boreal Shield East includes those with ecoregion numbers greater than 95. This Boreal Shield split is based on fire occurrence, with much more area burned in the Boreal Shield West area (Fig. 1).

2.2. Large-fire data base

For the current study, we extracted data on start location, start date, and final size for each fire. Unfortunately, the LFDB does not have data on the fire end date, so we have no record of the precise dates during which the fire spread. Also, the exact ignition date has some uncertainty although many agencies estimate this using both the date of detection and knowledge of recent weather to account for hold-over fires (especially for lightning-caused fires). Polygons that spatially delineate the outer perimeter of the fires are also available for part of the period. However, we did not use these in the present study because of some missing data and the limitations of other geographical data, such as changing fuel type patterns over time. The LFDB is currently being expanded to include pre-1959 and post-1995 fires, and future modifications to the 1959 to 1995 data may be slightly different from the data reported here.

Fig. 2. Canadian ecozones. The Boreal and Taiga Shield ecozones are split into east and west components.

2.3. Weather

Weather data are required to calculate Fire Weather Index (FWI) System components that relate to fire occurrence behaviour (Van Wagner 1987). This system uses relationships between weather and the moisture condition of fine, medium, and coarse fuels based on a long history of experiments and wildfire observations. Basic components can be calculated using noon-hour (local standard time) values of temperature, relative humidity, and wind speed, and daily total precipitation. The data were taken from Environment Canada surface observation stations that operated for a full fire season for at least part of the analysis period. We used noon observations from 415 hourly weather stations distributed across the country. Weather data from the Ontario Ministry of Natural Resources fire weather station archive from 1963 to present were also included to improve the weather station network coverage in the north of Ontario. Rainfall data from 90 stations in Environment Canada's daily climatological network were also used to augment the noon records in areas of the country prone to fire but with very sparse hourly weather station coverage. These weather and fire danger data were interpolated to each fire location within the LFDB for the start date and the following 20 days using a thin-plate cubic-spline technique (Flannigan and Wotton 1989).

2.4. Fuel types

Experimental data show that fuel consumption partly depends on fuel type (i.e., forest type), and we used the fuel-type classifications from the FBP System (Forestry Canada 1992). A data base of spatially explicit fuel types is not available for all of these fires. In recent years, many provincial agencies have developed fuel-type classifications based on stand inventory data that are incorporated into a GIS. Also, broad fuel types for all of Canada have been classified using advanced very-high resolution radiometer (AVHRR, nominal pixel size of 1 km^2) remote sensing for 1989 (EMR 1993) and 1995 (Beaubien et al. 1997). The difficulty is that these classifications are inappropriate for much of our study period since they often classify post-fire vegetation. For example, fire scars can be seen in the 1995 AVHRR imagery because of early post-fire successional vegetation that is deciduous, compared to surrounding unburned coniferous forest. Remote sensing data prior to 1959 and for about 10-year intervals would be needed to correctly classify fuels spatially and these data are not available. Also, spatially explicit fuel-type information still has limited usefulness unless detailed fire progression maps are available to relate fire spread to fuel type.

Given these difficulties, we did not colocate the pre-fire fuel type with each fire polygon. Instead, we classified the percentage of each fuel type present in each ecoregion. This was done using the AVHRR data and the National Forestry data base (NFD) (Lowe et al. 1996). We first classified the percentage of an ecoregion having the C1 fuel type (spruce–lichen woodland) using the 1989 AVHRR data. This fuel type only occurs in the more northern regions where ground-truthed NFD information is not available and the forests are not commercially harvested. In most cases, the same C1 fuel type regenerates following disturbance in these areas. In other areas, the NFD classifies forest types (deciduous, coniferous, mixed) for each ecoregion and estimates the percentage of forest for different tree genera. Excluding non-fuel areas (lakes, rock, agriculture), we classified the remaining fuel types as follows:

(1) C2 (boreal spruce) includes all coniferous forest types except those dominated by the genus *Pinus* or Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco).

(2) C3 (mature jack (*Pinus banksiana* Lamb.) or lodgepole pine (*Pinus contorta* Dougl. ex Loud.)) and C4 (immature jack or lodgepole pine) include all coniferous forest types with genus *Pinus*. We assume that 70% of this area is C3 and 30% is C4 assuming that C4 is typical for about the first 30 years of post-fire succession of pine forests and the fire cycle is of the order of 100 years.

(3) C7 (ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) – Douglas-fir) includes all coniferous forest types with genus *Pseudotsuga*. This forest type is restricted to western Canada (mostly British Columbia). We recognise that some ponderosa pine areas may be classified as C3 or C4, but this makes little difference at the national scale because only a small amount of area has burned in these regions.

(4) D (deciduous) includes all deciduous forest types. Leafless deciduous is assumed for fires starting before June 1 and after September 30, whereas leafed deciduous is used for the June 1 to September 30 period.

(5) M (boreal mixedwood) includes all mixed forest types. Leafless mixedwood is assumed for fires starting before June 1 and after September 30, whereas leafed mixedwood is used for the June 1 to September 30 period. In addition, the mixedwood type is further subdivided into three categories, because the percentage of coniferous fuels greatly affects fire behaviour. M25 (25% coniferous, 75% deciduous) includes mixedwood areas with <33% coniferous species. M50 (50% coniferous, 50% deciduous) includes mixedwood areas with ≥33% and ≤66% coniferous species. M75 (75% coniferous, 25% deciduous) includes mixedwood areas with >66% coniferous species.

Other fuel types used in the FBP System, such as red (*Pinus resinosa* Ait.) and eastern white pine (*Pinus strobus* L.) (C5), conifer plantation (C6), and slash cover a very small percentage of the country and are largely unaffected by the large fires, so were not included. We recognise that fuels are not static, especially since recent fire history determines stand age and composition in the boreal forest, but these are our best estimates of fuel types for the ecoregions.

2.5. Soils

Surface fuel consumption includes combustion of part of the top organic soil layer (duff), so information on soil parameters can help in the estimation of carbon loss. A data base of the soil landscapes of Canada has been derived based on Shields et al. (1991) (http://res.agr.ca/CANSIS/NSDB/SLC). In addition, peatlands have been classified in some parts of the country (Vitt et al. 1996), but a national data base of peatlands has not yet been completed. An additional data set on carbon inventories in forest soil has been compiled by Siltanen et al. (1997). We used these data bases to identify whether the fuel consumption estimates were consistent with duff layer inventories. We tested for the occurrence of shallow soils by evaluating whether a sufficient duff layer was available in various ecozones to sustain the predicted fuel consumption. This was done using the range of carbon inventories (i.e., kg C·m^{-2}) of Siltanen et al. (1997) for the organic horizons for each fuel type (based on dominant tree species). We also evaluated whether our fuel consumption predictions underestimated deep-burning fires in organic soils. This was done through a literature search of observations of fires in peatlands to compare to the depth-of-burn estimated in our analysis.

2.6. Fuel consumption and carbon emissions

For any given fire, we estimate fire fuel consumption (FFC; kg dry fuel/fire) as

$$[1] \qquad \mathrm{FFC} = \mathrm{TFC} \times A_{\mathrm{b}}$$

where TFC is mean total fuel consumption (kg dry fuel·m^{-2}) and A_{b} is the area burned by the fire (m^2). TFC is the sum of SFC and CFC, where SFC is the mean surface fuel consumed (kg dry fuel·m^{-2}) and CFC is the mean crown fuel consumed (kg dry fuel·m^{-2}). A_{b} is given in the LFDB, and we use the FBP System model to estimate SFC and CFC. SFC includes all surface fuels consumed, such as soil organic matter, coarse woody debris, and ground vegetation. SFC is a function of the Fine Fuel Moisture Code (FFMC) for the C1 fuel type and a function of the Buildup Index (BUI) for the other fuel types (C7 uses both FFMC and BUI). Both FFMC and BUI are outputs of the FWI System (Van Wagner 1987), based on the interpolated weather data (section 2.3). CFC is based on default values of crown fuel loads and estimates of the crown fraction burned, calculated from crown base height for each fuel type, the foliar moisture content, the SFC and the fire rate of spread (ROS). Equations for these parameters for each fuel type are given in Forestry Canada (1992).

The FBP model is used to calculate the daily fuel consumption for fuel type j, DFC$_j$ (kg·m^{-2}), using the weather data at noon. We first consider that fire spreads through different fuel types at different rates. For example, the ROS in a deciduous forest type is much slower than in the C2 fuel type for similar weather conditions. We assume that ROS is a reasonable parameter to distinguish fuel-type effects along a linear fire front of a large fire. Therefore, we define the fraction of fuel type j, FR$_j$, that contributes to DFC$_j$ as

$$[2] \qquad \mathrm{FR}_j = \frac{\mathrm{ROS}_j \times \mathrm{ffrac}_j}{\sum_j (\mathrm{ROS}_j \times \mathrm{ffrac}_j)}$$

where ffrac$_j$ is the fraction of fuel type j for a given ecoregion and ROS$_j$ is the fire rate of spread for fuel type j. We then calculate the final daily DFC for day i (DFC$_i$) by summing the adjusted values for each fuel type as

$$[3] \qquad \mathrm{DFC}_i = \sum_j (\mathrm{DFC}_j \times \mathrm{FR}_j)$$

As mentioned in Section 2.2, the fire end date is not included in the LFDB. Therefore, we estimated the mean value for DFC for the whole fire, TFC, based on an algorithm where the cutoff date of the fire is estimated when

$$[4] \qquad \mathrm{DFC}_{i+1} < \sum_{k=1}^{i} \frac{\mathrm{DFC}_k}{n}$$

where i is the day following (and including) the fire start date, and n is the number of days since the fire started to day i. This scheme ends the fire when TFC declines, reflecting weather events that slow the fire progression. This is a point where the fire is potentially extinguished by precipitation or when suppression activities may successfully hold fire growth. This weights the mean towards days when more fuel is consumed (i.e., the fire is spreading). This scheme is appropriate for small fires that spread for only a few days. However, infrequent large campaign fires that burn for many months may experience periods of intense fire activity interspersed with quiescent periods. The present scheme may define a fire period that is shorter than the actual burn period. For these cases, we assume that the subsequent periods of vigorous fire spread have similar DFC values as during the initial period of fire growth. We also used an absolute cutoff for TFC at 21 days following the fire start; although this was rarely invoked, it helped truncate some situations where TFC climbed very slowly. It is important to note that eq. 1 only relies on the correct mean value of SFC and CFC, and not on the burning period. For 445 fires where start dates are not available (mostly in the 1970s in the Boreal Shield West and Boreal Plains), we used the mean TFC value from the respective ecozone to estimate carbon loss. For the approximately 200 fires where locations were not available but the province was known, we assigned them to the most likely ecozone where fires occurred.

Direct carbon emissions are calculated as 0.5 kg C·kg total dry fuel consumed^{-1}. For the 1996–1999 fires, we estimated carbon emissions using the mean TFC for the 1959–1995 period.

3. Results and discussion

3.1. Area burned

The LFDB includes 11 423 fires that burned 77 × 10^6 ha in the 1959–1995 period (Table 1). The mean fire size was 6754 ha, the median is 960 ha, with maximum and minimum fires sizes of 1 050 000 and 200 ha, respectively. The area burned by large fires (≥200 ha) likely represents about 97% of the total area burned by all fires, based on known distributions of fire size (Stocks 1991). The area burned varies greatly among years, ranging from a minimum of 0.3 × 10^6 ha in 1978 to 7.5 × 10^6 ha in 1989. The Taiga Shield

Table 1. Area burned (km^2) by fires ≥2 km^2 in size in each ecozone.

Year	Southern Arctic	Taiga Plains	Taiga Shield West	Taiga Shield East	Boreal Shield West	Boreal Shield East	Atlantic Maritime
1959	0	767	14	0	146	1 234	2194
1960	0	103	379	0	3 311	3 307	419
1961	0	1 849	1 783	176	7 375	4 720	99
1962	13	200	22	419	118	5 072	62
1963	26	156	51	183	564	4 885	302
1964	0	54	1 789	22	6 591	1 924	38
1965	0	275	5	0	113	1 365	381
1966	0	1 298	988	22	172	1 808	66
1967	0	392	58	62	1 382	3 831	28
1968	351	1 895	41	16	163	2 970	1460
1969	0	4 929	231	70	841	573	101
1970	0	832	2 831	150	10 143	2 272	423
1971	0	4 102	4 621	0	949	17 269	121
1972	41	2 153	363	129	1 920	867	8
1973	13	2 018	2 727	2 013	3 865	92	0
1974	14	156	0	1 502	6 638	1 138	0
1975	0	4 902	957	419	1 295	2 082	10
1976	9	2 982	4 049	2 193	6 443	11 417	4
1977	0	1 606	1 312	6	4 685	937	0
1978	0	71	763	14	945	107	22
1979	81	11 628	18 407	10	4 049	336	0
1980	3	10 881	3 747	81	18 832	195	26
1981	0	12 740	2 116	581	22 622	939	0
1982	0	4 645	949	263	667	125	53
1983	0	2 196	157	3 167	5 566	6 298	6
1984	0	1 009	512	24	3 983	89	0
1985	0	138	2 260	1 385	743	501	17
1986	0	3 127	58	142	1 477	2 834	374
1987	101	4 170	322	50	3 610	470	22
1988	19	621	122	2 487	8 087	320	16
1989	15	2 620	7 545	20 564	27 622	249	0
1990	0	1 192	132	389	2 625	406	72
1991	275	179	3 852	686	4 051	4 180	35
1992	9	21	1 881	68	4 053	364	48
1993	0	8 145	988	486	4 598	1 054	3
1994	16	16 334	29 155	2 176	8 211	95	0
1995	0	30 014	96	1 993	19 992	2 891	265
1996							
1997							
1998							
1999							
Mean	27	3 795	2 575	1 134	5 360	2 411	180

Note: Data for 1996–1999 are national totals from the Canadian Interagency Forest Fire Centre (Winnipeg, Man.).

West ecozone typically has the greatest area burned. The burned areas in Table 1 differ from statistics given by CCFM (1997), with the LFDB having about 13% more area burned in the 1970 to 1995 period. This is mostly caused by differences in the 1970s where the LFDB has more fires than the CCFM (1997) statistics. In addition, we have aggregated statistics on area burned for 1996–1999 (Canadian Interagency Forest Fire Centre, Winnipeg, Man.), which are presently being added into the LFDB.

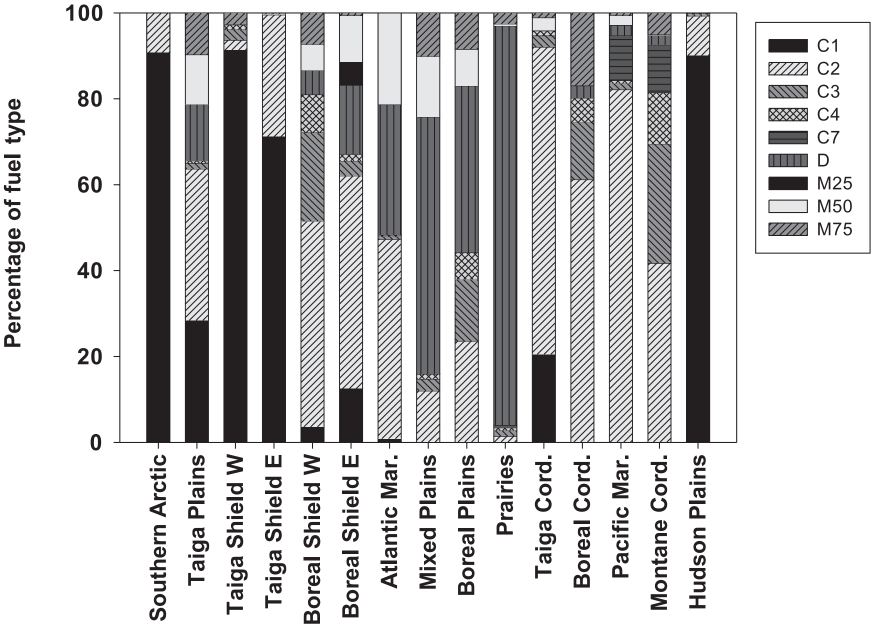
The estimates of area burned are provided by each agency (provincial, territorial, federal) responsible for the land base. These estimates are based on aerial photography, perimeter surveys (recently using an airborne global positioning system, GPS), or satellite imagery (in the case of some 1989 Manitoba fires). The more recent estimates tend to be more accurate, especially when airborne GPS is used because the surveyor can see areas burned by surface fires that may not have killed the tree canopy. However, most of the large fires in the boreal forest cause tree mortality. In more recent years, fire mapping excludes the larger unburned islands within the fire from the area-burned statistics. However, this depends widely on individual fires and agencies. Eberhart and Woodward (1987) estimated that 4–5% of the area in 41 fires greater than 200 ha in size in northern Alberta between

Mixedwood Plains	Boreal Plains	Prairies	Taiga Cordillera	Boreal Cordillera	Pacific Maritime	Montane Cordillera	Hudson Plains	Total
26	509	0	83	328	0	283	0	5 585
74	276	2	72	20	26	969	0	8 958
62	7 503	398	0	1588	144	2577	62	28 335
120	583	4	90	95	10	33	0	6 841
263	143	120	56	118	12	10	14	6 902
0	1 675	112	0	9	0	0	176	12 390
44	723	45	47	482	50	223	0	3 752
4	212	3	10	1766	5	7	0	6 362
2	649	39	103	1098	89	695	0	8 428
12	4 720	46	0	162	5	10	0	11 850
35	312	0	850	6158	22	196	0	14 318
30	2 739	2	0	243	24	449	0	20 138
26	2 120	6	326	3137	66	955	279	33 976
0	589	6	237	447	34	24	1869	8 688
0	253	21	0	11	7	242	144	11 404
0	178	52	15	16	3	99	70	9 882
9	80	6	174	105	0	25	49	10 112
0	743	9	24	488	0	8	384	28 753
0	1 985	382	2309	484	0	11	301	14 018
0	286	2	54	305	53	73	0	2 696
0	1 460	0	65	25	18	87	14	36 180
0	11 485	540	8	1626	0	64	75	47 564
0	16 503	4404	0	498	9	160	607	61 175
0	4 839	0	345	4971	8	100	0	16 974
0	251	37	137	762	0	209	1026	19 812
0	990	271	70	116	0	49	18	7 129
0	248	0	29	2027	45	947	0	8 339
0	73	0	281	681	12	56	50	9 165
0	1 110	3	259	6	26	222	25	10 395
0	992	124	37	15	0	46	162	13 048
0	8 299	27	325	2898	23	54	4590	74 829
0	1 363	13	939	862	78	37	705	8 814
3	668	8	85	1148	0	104	523	15 676
0	289	0	66	426	4	54	908	8 190
0	3 579	0	307	237	0	0	8	19 406
0	156	0	847	3846	6	202	351	61 393
0	12 022	0	86	3408	10	26	2553	73 352
								18 780
								6 250
								47 108
								17 056
19	2 449	181	225	1098	21	251	406	20 342

1970 and 1983 consisted of unburned islands. Kafka et al. (2001) estimated that less than 3% of a 49 000 ha 1995 fire in Quebec consisted of unburned islands. In some cases, areas identified as unburned islands may have experienced some surface fire, but true unburned islands exist within fires. In addition, each fire has a range of burn severities, but we partially account for this through the estimates of fuel consumption. From these two studies, it is likely that taking unburned islands into account would decrease the area burned by only 3–5%.

In most cases, large lakes and non-fuel areas are excluded from the area-burned estimates. However, small areas of open water (including open fens and marshes) and bare rock are included. This error is likely greatest in the Boreal and Taiga Shield ecozones where these features are most common. It is difficult to estimate the extent of these non-fuel areas because the area increases with the scale of the analysis; i.e., it poses a fractal problem. In addition, the exclusion of non-fuel areas within the burn perimeter varies among agencies, years and regions. For example, in areas of high timber value, more accurate estimates are made to account for timber loss. This is not required for fires in non-harvested sparse forests in the north. In addition, agencies have not targeted area-burned estimates for carbon account-

Fig. 3. Percentage of each FBP System fuel type within each ecozone. Only forested areas are included. The definitions of the fuel types are given in the text.



ing, so excluding non-fuel areas is a low priority. We made a rough estimate of this potential problem by overlaying a data base of Canadian lakes (ESRI 1993; minimum lake size 0.1 ha) on fire polygons for Ontario, Manitoba, and Saskatchewan for 1981 and 1994. This covers fires that burned about 3.2 × 10^6 ha, and includes the Canadian Shield where the lake effect is likely greatest. We then compared the fire polygon areas minus the lake areas using a GIS against the estimate of area burned by the provincial agencies (A_b) for each of these fires (i.e., the two estimates used the same fires). The provincial estimates were 15% greater than this polygon integration, caused mostly by differences in a few large fires in some areas. There was very close agreement (about 1% difference) for other areas. We believe that additional quantitative work is warranted in this area, targeted at carbon emission estimates. However, it is likely that the country-wide potential overestimate is less than 5%, although highly variable among years and areas.

Another source of inaccuracy in A_b is caused by rounding of the fire perimeters during mapping. Again, this varies greatly among years, areas, agencies, and groups involved in the estimation. High-value timber productive areas generally have better estimates. Areas estimated from detailed aerial photography or from a helicopter using GPS are likely better than some approximate sketches done by operational field crews during busy fire seasons. There may also be some rounding during the digitizing process of some fires. At present, we do not have a quantitative estimate of this error, but recognise that it exists. For bounding estimate purposes, we suggest a ±5% uncertainty in fire areas caused by edge effects.

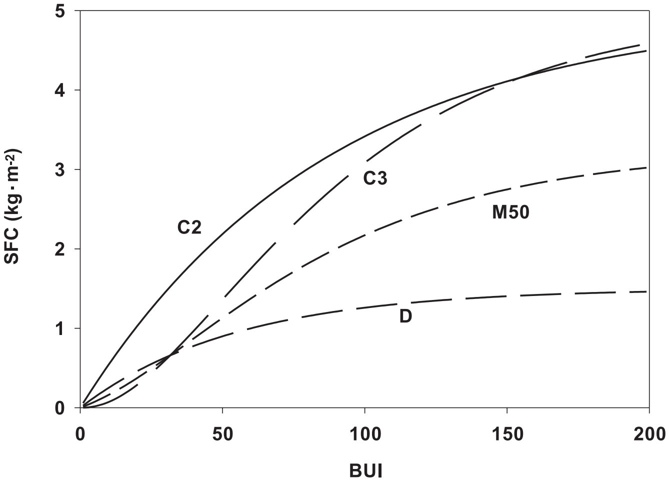
Inaccuracy in estimating A_b directly affects fuel consumption estimates through eq. 1. We suggest that the LFDB underestimates A_b by 3% by excluding fires smaller than 200 ha in area, overestimates A_b by 2–5% because of unburned islands, overestimates A_b by less than 5% because of non-fuel areas, and estimates A_b by ±5% because of edge effects. In addition, we believe that some fires may be missed but do not have a quantitative estimate of these. For bounding purposes, we use an additional 5% area burned for possible missed large fires during the 1959–1969 period. It is likely that missed large fires during the post-1969 period account for only about an additional 1% of area burned because large fires seldom escape detection, especially since the launch of earth-observing satellites. Undetected small fires contribute little to the area burned.

3.2. Fuel types

Each ecoregion was partitioned into fuel types and the distribution for each ecozone was calculated by summing the areas of each fuel type for the ecoregions within an ecozone (Fig. 3). The boreal and taiga areas have the largest area burned (Table 1) and these are dominated by C1 and C2 fuel types. Ecozones with large deciduous components, such as the mixedwood plains, have a much smaller area burned. The Boreal Shield West has a larger pine component (C3 and C4) than the Boreal Shield East.

The impact of fuel type on SFC is shown in Fig. 4 where four fuel types are compared for a range of BUI values. Our weather data calculated BUI values ranging from 1 to over 300 with a median of 60 for the fire days. It is clear that the coniferous fuels (C2, C3, C4) dominate SFC compared with deciduous fuels (D) with mixedwood fuel types having intermediate values. There is some error in our allocation of fuel types because canopy structure is better than species as an indicator of fire behaviour. We therefore expect some trade-off between coniferous areas that are classed as C2 but should more correctly be classed as C3. For SFC, this difference is very small at BUI values greater than 100, but C2 has about 0.5 kg·m^{-2} more SFC than C3 at BUI = 20

Fig. 4. Surface fuel consumption (SFC) estimates from the FBP System models for boreal spruce (C2), jack or lodgepole pine (C3), 50% leafless mixedwood (M50), and leafless deciduous (D). BUI, Buildup Index.



(Fig. 4). Mean crown fuel loads for C3 are about 0.35 kg·m^{-2} greater than C2 (Forestry Canada 1992), so in a crown fire (generally at higher values of BUI), the overall effect is for more fuel consumption in the C3 fuel type. This trade-off between SFC and CFC probably results in only a small error (<0.2 kg·m^{-2}) in overall fuel consumption for a large population of fires, if these two fuel types are incorrectly classified.

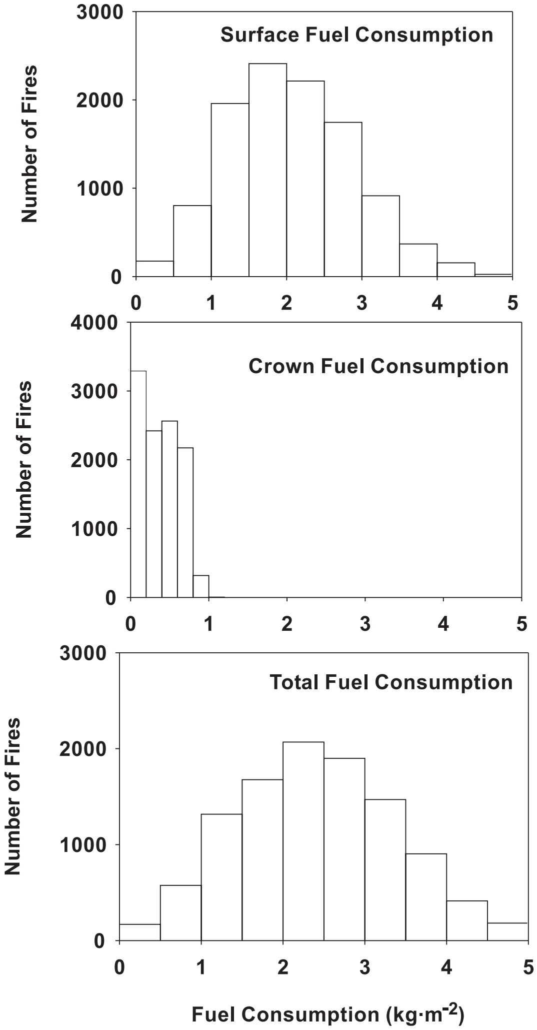
The available fuel inventories likely bias towards younger vegetation types, missing some of the older stands that occurred before the fire. In some areas in some years, we may have overestimated the deciduous component and underestimated SFC (Fig. 4). This error would be greatest in ecoregions where the fire cycle has drastically increased over the study period.

3.3. Weather

The interpolated weather data are our best approximations to conditions at the fire site. In most cases, the temperature data are reasonable approximations since temperature does not vary greatly over space. However, localized precipitation during convective storms causes errors that increase with the distance between weather stations. Topographical variations can also cause errors in wind speed estimates, especially in rugged terrain.

We also have uncertainties related to start date for some fires. In most cases, the fire start date is well known, and our weather data confirm that the FWI System codes are conducive to fire growth. For example, 90% of the fire days had Initial Spread Index (ISI; an FWI index that combines wind and the condition of fine-textured fuels) values greater than two, indicating some fire growth. Days with lesser fire growth are a combination of quiescent periods and potential differences between the interpolated weather data and the actual weather at the fire site. A small percentage reflect potential errors in the recorded start date, but this is likely only a few percent of the total number of fires. In these cases, we would underestimate TFC. There is a lesser problem with incorrect start dates contributing to overestimates of TFC because large TFC values reflect severe fire weather when it is likely that the fire was active.

Fig. 5. Frequency of occurrence of surface fuel consumption (SFC), crown fuel consumption (CFC), and total fuel consumption (TFC) for 10 771 fires, 1959–1995.



3.4. Fuel consumption

Figure 5 shows the frequency distribution of SFC, CFC, and TFC for all fires in the period. The overall mean value for SFC is 2.1 kg·m^{-2}, with 97% of the values lying between 0.5 and 4.0 kg·m^{-2}. Crown fuels also become part of the TFC when the ISI values increase, and add an average of 0.37 kg·m^{-2}. About 88% of the fires had some crown fuel consumption. TFC for each ecozone is shown in Table 2 for the whole period. The highest TFC values are for the Western Cordilleran ecozones because of the very dry conditions experienced during these fires. The lowest TFC is for the Prairies ecozone because of the deciduous fuel type. Prairie grass fires are excluded from this data base except where they enter a forest protection zone. Through the Boreal and Taiga ecozones, TFC values are typically in the range of 1.8–2.9 kg·m^{-2}. Weighting all fires equally, the mean TFC is 2.4 kg·m^{-2} with 87% of the values between 1 and 4 kg·m^{-2}. Weighting by area burned, the mean estimate of TFC for all

Table 2. Mean total fuel consumption by individual fire for each ecozone, 1959–1999.

Ecozone	Total fuel consumption (kg·m^{-2})	No. of fires
Southern Arctic	2.3±0.81	27
Taiga Plains	2.86±0.75	1094
Taiga Shield West	1.85±0.71	1006
Taiga Shield East	1.93±0.71	396
Boreal Shield West	2.47±0.82	2576
Boreal Shield East	2.01±0.75	2030
Atlantic Maritime	1.81±0.64	215
Mixedwood Plains	1.64±0.50	66
Boreal Plains	2.35±0.99	1390
Prairies	1.09±0.74	105
Taiga Cordillera	3.06±1.07	192
Boreal Cordillera	3.23±0.89	687
Pacific Maritime	3.3±0.96	107
Montane Cordillera	3.9±1.07	647
Hudson Plains	1.86±0.72	233
All Canada	2.44±1.00	10771

Note: Values for total fuel consumption are means ± 1SD.

Canadian fires from 1959 to 1995 is 2.6 kg·m^{-2}; this mean better reflects the impact on the full landscape. However, Table 2 shows that different TFC values should be used for the various ecozones. Previous estimates of 2.5 kg·m^{-2} have been used for Canadian boreal forests (Stocks and Kaufmann 1997).

We tried variations on our scheme to estimate TFC. For example, using the maximum TFC value for any day during the estimated burning period, increases mean TFC from 2.4 to 2.9 kg·m^{-2}. If we select the fuel type in each ecoregion that gives the maximum TFC, the mean estimate is 2.8 kg·m^{-2}. If we weight the TFC by fuel type only, without including ROS as in eq. 2, the estimate is 2.0 kg·m^{-2} because of a larger deciduous component weighting. We believe that the scheme we have selected gives the best estimate of TFC given the limitations of the data.

The SFC equations for the FBP fuel types were derived using a combination of field data (experimental prescribed fires and wildfires), curve fitting, and expert opinion. There is no significant difference between the equations and the data ($P > 0.1$, paired t test; SYSTAT 1997). We estimated the variability between the equations and data as the percentage standard deviation from the mean (based on mean square differences between the data and equations) as 15% for C1 ($n = 7$), 34% for C2 ($n = 12$), 37% for C3 ($n = 33$), 20% for C4 ($n = 13$), and 55% for D (leafless) ($n = 25$). Most of the area burned is in the coniferous fuel types, and we estimate the overall variability between the equations and the data at about 35% (±1 SD). The data cover BUI values of less than 80, and we cannot quantitatively evaluate the uncertainty in extrapolating beyond this. However, the equations level off and reach an asymptote for SFC at about 5 kg·m^{-2} (BUI > 200).

The CFC increases with ISI until a crown fire ensues, with potentially all of the crown consumed. The values for crown fuel load (kg·m^{-2}) are 0.75 for C1, 0.8 for C2 and mixedwood, 1.15 for C3, 1.2 for C4, and 0.5 for C7 (Forestry Canada 1992). Crown fires are extremely rare in the deciduous fuel type. The variability in crown fuel load for a given site is about 15% for C3 and C4 fuel types (Stocks 1987, 1989). It is likely that this is more variable over the general landscape for a given fuel type, especially in areas with only partial crown closure, which may be closer to a C1 fuel type. However, the error caused by this variability is less than that for SFC.

The availability of fuel over the general landscape is another issue. The experimental data used to derive the FBP System were based on relatively uniform fuel type assemblages. We believe that these may represent close to mean conditions for SFC. However, there are areas of very shallow soils, especially on the Canadian Shield, where the SFC could be limited by availability. Our maximum SFC was 4.7 kg·m^{-2}, with only 1.7% of the fires (5% of area burned) having SFC >4 kg·m^{-2}. The data base of Siltanen et al. (1997) indicates that all ecozones have some portion of their area with surface organic layers in excess of 6 kg dry biomass·m^{-2}. Although we have not matched the fires spatially to soil maps, we believe that our model does not unreasonably consume fuels that are not available. Another possibility is that fires burn much deeper in organic soils than the model predicts. There is no doubt that organic soils dominate large parts of the landscape where fires occur (Vitt et al. 1996). Fires usually consume peat soils to depths less than 10 cm (Zoltai et al. 1998) although some deep-burning fires consume the top 20 cm (Dyrness and Norum 1983), and there are accounts of peat burning down to 1 m (Zoltai et al. 1998). Our maximum value of about 4.7 kg·m^{-2} represents a depth of burn of less than 8 cm for bog peat and 5 cm for permafrost peat (based on bulk densities from Zoltai et al. 1998). However, only about one-third of all bogs and swamps have combustible surfaces down to about 9 cm, and a much smaller fraction are ignitible. This is complicated by areas of standing water and wet peat that do not burn. The overall impact at the landscape scale is uncertain, but if about two-thirds of peatlands do not burn, then the maximum SFC value, which underestimates in dry peat, could be a reasonable average for all peatlands. For comparison, Kasischke et al. (2000) estimated a maximum of 4.2 kg C·m^{-2} (i.e., about 8.4 kg fuel·m^{-2}) consumed in some severe Alaskan fires although most fires released less.

3.5. Direct carbon emissions for ecozones

Our best estimates of annual emissions for each ecozone are presented in Table 3, and summarised for the 1959–1999 period in Fig. 6. The annual mean for this period is 27 Tg C·year^{-1} with a range of 3 to 115 Tg C·year^{-1}. It is important to note that carbon emissions are highest in 1995, even though slightly more area was burned in 1989. This is caused by the location of the fires and fire weather, with slightly greater fuel consumption during 1995. There tends to be an increase in emissions over this period with mean releases of 13 Tg C·year^{-1} in 1959–69, 22 Tg C·year^{-1} in 1970–1979, 37 Tg C·year^{-1} in 1980–1989, and 39 Tg C·year^{-1} in 1990–1999.

We also present upper and lower bounding estimates of carbon emissions. We recognise that uncertainty varies among fires with some relationship that depends on year and area, and sometimes among individual fires. However, we do not have quantitative data to calculate uncertainties for each fire, so we apply our best estimate of overall bounds to the whole data base.

The upper bound allows the following:

(1) Area burned increases by 9% (1970–99) to 13% (1959–69) to account for fires smaller than 200 ha (3%), some possible missing fires in the data base of 5% from 1959 to 1969 and 1% after 1969, and underestimates of complex fire edges (5%).
(2) TFC increases by 8% to account for variability between the FBP System fuel consumption equations and the experimental data estimated as 1 SE from the calculated SD of ±35% and a mean experimental data population of 18 fires for each fuel type (see section 3.4)

The lower bound allows the following:

(1) Area burned decreases by 15% to account for unburned islands (5%) and non-fuel areas (5%) that were not mapped, as well as over-estimates of fire areas because of complex edges (5%).
(2) TFC decreases by 8%, again to account for variability between the FBP System fuel consumption equations and the experimental data.

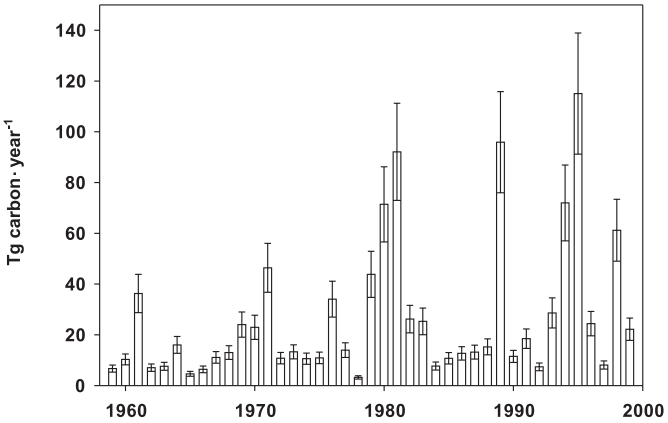
Using these estimates, the overall range in the mean annual carbon emission is 22 to 33 Tg C·year^{-1}, or about ±6 Tg C·year^{-1}. For comparison, French et al. (2000) calculated an average weighted emission of 53 Tg C·year^{-1} for the whole North American boreal forest (including Alaska) for the 1980–1994 period.

3.6. Impact on the carbon balance of Canadian forests

Fire disturbance is a key part of models of the carbon balance for the Canadian forest (Kurz and Apps 1999; Chen et al. 2000). These models use area-burned statistics and some estimate of carbon losses during fires. For example, the model of Kurz et al. (1992) uses a disturbance matrix that assumes a certain portion of soil and biomass carbon is released, giving a carbon emission loss of 1.3 kg C·m^{-2}, identical to the mean area-weighted value in the present study. Changes to the TFC values only slightly affect the overall carbon balance because of the over-riding variation in area burned among years (Fig. 6). A sensitivity analysis by Kurz and Apps (1994) indicates that increasing area burned by a factor of three decreases the total forest carbon budget by only 6% over 100 years. However, it is clear that several years with greater amounts of fire can easily drive the carbon budget down, even causing a situation where the forest is a net carbon source (Kurz and Apps 1999).

Our present analysis gives direct carbon losses from fire. Models estimate that only about half of the carbon loss from a fire occurs through direct emissions, with the remainder lost through slower decomposition processes over a period of years (Auclair and Carter 1993; Dixon and Krankina 1993; Kasischke et al. 1995; Kurz and Apps 1999). However, the magnitude of post-fire losses is poorly known with few direct measurements. In addition, the burned boreal landscape takes two to three decades to recover to the sink strength of the more mature forest (Amiro et al. 1999, 2000). Hence the overall impact of fire on the carbon budget is magnified, and is included in many models (Kasischke et al. 1995; Kurz and Apps 1999).

Fig. 6. Direct carbon emissions from fires for all Canada, 1959 to 1999. Error bars are estimated bounds of uncertainty.



The apparent increase in direct carbon emissions from fires in the last decade or so may not be a short-term anomaly. This recent increase is probably driven by weather, and projections indicate that global warming may continue this increase. Recently, the Canadian Regional Climate Model has been used to predict possible changes to fire weather in a 2 × CO$_2$ scenario compared to present day (Wotton et al. 1998). For much of the western Canadian boreal forest fire season, temperature is predicted to increase, perhaps as much as 5°C, while precipitation may decrease by as much as 20%. Overall, the Fire Weather Index is expected to increase in many areas by more than 20%, indicating weather more conducive to fire activity. In contrast to the predictions of increased fire activity in western Canada, it is possible that parts of eastern Canada may experience less fire because of more precipitation in a warmer climate (Flannigan et al. 1998). In addition, a 2 × CO$_2$ environment is expected to directly affect vegetation, although there are a range of predictions of forest responses (e.g., IPCC 1998). Although species migration may not follow these climatic drivers directly, the message is that different fuels could predominate in a different future climate, which will impact fire behaviour.

The mean direct carbon emissions from fires is 27 Tg C·year^{-1} which is 18% of the approximately 150 Tg C estimated to be annually released as CO$_2$ from the Canadian energy industry from all current sources, including transportation (Analysis and Modelling Group 1999). If the goal is to reduce fire to help meet Canada's commitments for the Kyoto Protocol, then the maximum contribution from fire would be 18% of the energy sector if there were no forest fires during the period of compliance, compared with the whole 1959–1999 period. If compared to fire emissions only in 1990 (i.e., the base year for the Kyoto Protocol), then 11 Tg C would be saved, or 7% of the energy sector contribution. Despite such calculations, it is impossible that all fires could be excluded from the Canadian forest. Current suppression efforts are substantial, and countrywide efforts at fuel management are unlikely to be successful at decreasing total area burned in the next few decades because of the

Table 3. Direct carbon emissions (Gg C·year^{-1}) from Canadian fires for each ecozone.

Year	Southern Arctic	Taiga Plains	Taiga Shield West	Taiga Shield East	Boreal Shield West	Boreal Shield East	Atlantic Maritime
1959	0	1 031	17	0	103	1 217	2789
1960	0	132	295	0	3 585	3 306	393
1961	0	2 596	1 539	91	8 329	5 500	62
1962	7	168	14	238	120	5 570	44
1963	0	216	73	167	947	5 161	326
1964	0	49	2 092	15	9 368	1 584	24
1965	0	352	0	0	120	1 504	403
1966	10	1 551	419	18	171	1 454	61
1967	0	569	41	64	1 458	4 443	24
1968	253	3 522	36	8	93	3 244	1216
1969	0	7 219	220	31	674	408	100
1970	0	1 286	2 750	113	12 479	1 631	336
1971	0	6 718	7 480	0	1 143	19 494	96
1972	31	2 919	349	104	2 335	1 014	9
1973	1	2 873	2 486	2 083	4 783	92	0
1974	17	157	0	928	8 168	745	0
1975	0	6 338	865	221	1 530	1 331	9
1976	6	4 105	2 598	2 455	8 451	14 815	3
1977	0	2 553	1 135	8	3 830	1 229	0
1978	0	70	710	16	1 097	80	28
1979	97	16 371	19 515	9	5 096	315	0
1980	0	17 106	4 705	33	27 274	192	16
1981	0	21 436	2 561	597	30 958	1 033	0
1982	0	6 776	869	168	553	149	56
1983	0	3 454	135	3 496	8 767	6 243	4
1984	0	1 109	337	9	4 293	71	0
1985	0	193	2 283	1 532	698	504	10
1986	5	4 700	42	108	2 010	3 588	381
1987	149	6 789	320	38	3 643	389	16
1988	27	501	71	2 181	10 260	357	14
1989	20	3 186	6 547	27 481	40 539	225	0
1990	0	1 811	108	257	3 369	411	45
1991	246	223	4 580	556	3 690	5 752	38
1992	0	21	1 228	52	3 870	364	54
1993	11	12 509	1 008	449	6 777	1 000	2
1994	19	20 211	30 385	1 762	9 798	91	0
1995	0	51 456	89	1 999	30 859	3 228	339
1996							
1997							
1998							
1999							
Mean	25	5 737	2 646	1 278	7 061	2 641	186

Note: The 1996–1999 data use the average fuel consumption for the 1959–1995 period (1.3 kg C·m^{-2}).

huge scale of the Canadian forest (Amiro et al. 2001). Fire is likely to be as predominant over the next few decades as it has been during the 1990s, with the more likely scenario to be increased fire caused by global warming. Compounding this issue is the recognition that fire is an important ecological factor in the boreal forest, and its exclusion (if possible) would severely affect historical landscape patterns, nutrient regimes, and biodiversity (Weber and Stocks 1998). Hence, efforts to decrease fire below historical regimes would negatively affect the Canadian boreal forest. Perhaps a more important question is what the boreal landscape will look like with increased fire and changes in species composition caused by climate warming.

4. Conclusions

Direct carbon emissions from large Canadian forest fires averaged 27 ± 6 Tg C·year^{-1} for the 1959–1999 period. However, individual years ranged from 3 Tg·year^{-1} in 1978 to 115 Tg·year^{-1} in 1995. Additional fires less than 200 ha in size likely increase these emissions by a few percent. These direct emissions by forest fires represent a significant part of

Mixedwood Plains	Boreal Plains	Prairies	Taiga Cordillera	Boreal Cordillera	Pacific Maritime	Montane Cordillera	Hudson Plains	Total
22	448	0	99	565	0	396	0	6 687
65	230	1	57	29	58	2162	0	10 313
45	9 021	283	0	3 026	262	5493	38	36 287
89	590	2	82	48	15	57	0	7 045
219	158	49	85	137	14	8	18	7 607
0	2 702	54	0	1	0	0	128	16 016
35	734	13	74	911	67	400	0	4 615
3	259	1	16	2 410	5	9	0	6 387
1	788	38	180	1 762	147	1578	0	11 094
6	4 325	11	0	248	11	18	0	12 994
25	459	0	1841	12 575	30	442	0	24 022
27	3 016	2	0	294	51	966	0	22 949
26	3 195	2	590	5 625	96	1791	136	46 395
0	674	3	388	655	40	48	2231	10 800
0	209	8	0	16	11	555	173	13 291
0	284	28	26	17	7	157	62	10 597
8	102	2	202	174	0	48	75	10 905
0	819	6	45	216	0	7	541	34 067
0	1 952	195	1866	926	0	14	259	13 967
0	356	1	86	542	112	123	0	3 223
0	2 110	0	34	41	30	182	14	43 816
0	18 970	273	5	2 649	0	80	99	71 402
0	28 196	5251	0	992	11	280	784	92 099
0	7 405	0	419	9 603	13	177	0	26 188
0	293	14	246	1 142	0	316	1188	25 299
0	1 265	342	15	161	0	79	4	7 684
0	364	0	39	3 034	98	2000	0	10 755
0	75	0	465	1 139	20	96	57	12 687
0	1 090	1	284	5	45	385	16	13 170
0	1 528	47	34	24	0	70	137	15 253
0	8 046	16	597	4 995	15	93	4133	95 894
0	2 315	6	987	1 376	164	42	607	11 498
3	697	3	115	1 889	0	197	482	18 481
0	276	0	109	659	8	102	637	7 382
0	6 018	0	500	337	0	0	7	28 617
0	179	0	1639	7 207	11	421	235	71 959
0	18 261	0	88	5 713	19	44	2951	115 046
								24 414
								8 125
								61 240
								22 173
16	3 444	180	303	1 923	37	509	406	26 645

the carbon budget for Canada, ranging annually from about 2 to 75% of CO_2 emissions from all energy sources with a mean of 18%. Post-fire effects also cause additional carbon releases through decomposition, and changes to the forest affect the strength of the forest carbon sink. Fire emissions have been generally increasing over the past two decades and are likely to remain high because of anticipated changes to fire weather caused by climate warming. We believe that historical and future carbon emission estimates can be improved and uncertainties reduced through better estimates of pre-fire fuels and post-fire analyses that include burn severities, unburned islands, and non-fuel areas. For part of the record, LANDSAT classifications with ground-truth data could contribute to mapping these large fires. However, actual measurements of fuel consumption are also needed, which would demand an improved system of carbon accounting following fires.

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