Future emissions from Canadian boreal forest fires

B.D. Amiro, A. Cantin, M.D. Flannigan, and W.J. de Groot

Abstract: New estimates of greenhouse gas emissions from Canadian forest fires were calculated based on a revised model for fuel consumption, using both the fire fuel load and the Drought Code of the Canadian Forest Fire Weather Index System. This model was applied to future climate scenarios of $2{\times}CO_2$ and $3{\times}CO_2$ environments using the Canadian Global Climate Model. Total forest floor fuel consumption for six boreal ecozones was estimated at 60, 80, and 117 Tg dry biomass for the $1{\times}CO_2$, $2{\times}CO_2$, and $3{\times}CO_2$ scenarios, respectively. These ecozones cover the boreal and taiga regions and account for about 86% of the total fire consumption for Canada. Almost all of the increase in fuel consumption for future climates is caused by an increase in the area burned. The effect of more severe fuel consumption density (kilograms of fuel consumed per square metre) is relatively small, ranging from 0% to 18%, depending on the ecozone. The emissions of greenhouse gases from all Canadian fires are estimated to increase from about 162 Tg·year^{-1} of CO_2 equivalent in the $1{\times}CO_2$ scenario to 313 Tg·year^{-1} of CO_2 equivalent in the $3{\times}CO_2$ scenario, including contributions from CO_2, CH_4, and N_2O.

Résumé : De nouvelles estimations des émissions de gaz à effet de serre provenant des incendies de forêt au Canada ont été calculées sur la base d'un modèle révisé de consommation des combustibles en utilisant à la fois la charge de combustible et l'indice de sécheresse de la méthode canadienne de l'indice forêt-météo. Ce modèle a été appliqué aux scénarios climatiques futurs dans un environnement contenant deux ($2{\times}CO_2$) ou trois ($3{\times}CO_2$) fois la quantité normale ($1{\times}CO_2$) de CO_2 en utilisant le modèle climatique mondial canadien. La consommation totale de combustibles de la couverture morte pour six écozones boréales a été estimée à 60, 80 et 117 Tg de biomasse sèche respectivement pour les scénarios $1{\times}CO_2$, $2{\times}CO_2$ et $3{\times}CO_2$. Ces écozones couvrent la région boréale et celle de la taïga et représentent environ 86 % de la consommation totale de combustibles par le feu au Canada. Presque toute l'augmentation de la consommation de combustibles dans les conditions climatiques futures est causée par une augmentation de la superficie brûlée. L'effet d'une plus forte densité de consommation de combustibles (kilogrammes de combustibles consumés par mètre carré) est relativement faible, variant de 0 à 18 % selon l'écozone. On estime que les émissions de gaz à effet de serre provenant de tous les incendies au Canada augmentent de 162 Tg en équivalent CO_2·an^{-1} environ avec le scénario $1{\times}CO_2$ à 313 Tg en équivalent CO_2·an^{-1} avec le scénario $3{\times}CO_2$, incluant la contribution du CO_2, du CH_4 et du N_2O.

[Traduit par la Rédaction]

Introduction

Fire burns about 20 000 to 30 000 km^2 of forest annually in Canada, with about 88% of this in the boreal and taiga forest regions (Stocks et al. 2002). This represents an average of 0.7% of the boreal and taiga forest being burned annually. The area burned in Canada has been increasing over time (Podur et al. 2002), with the last two decades having about double the area burned compared with the previous two decades (Stocks et al. 2002). Fire is a major driver of the carbon balance in Canada's forests through its role in forest renewal and determination of the age of forest stands (Kurz and Apps 1999; Harden et al. 2000; Bond-Lamberty et al. 2007; Kurz et al. 2008).

The impact of fire on the carbon cycle, with subsequent climate change implications, can be separated into two major processes. First, carbon is released during the fire through combustion. Much of this carbon is lost as carbon dioxide (CO_2), but substantial amounts of carbon monoxide (CO) and methane (CH_4) can also be released (Cofer et al. 1998; Rinsland et al. 2007). These direct releases contribute to increases in greenhouse gases in the atmosphere and cause pollution episodes in the downwind smoke plume (Wotawa and Trainer 2000; Forster et al. 2001; Park et al. 2003). The second major process is the carbon dynamics of the postfire forest. This process involves a young growing forest that has a changing rate of net ecosystem production (NEP) as it develops towards maturity. In general, young forests have lower NEP than intermediate-aged and older forests (Amiro 2001; Litvak et al. 2003; Coursolle et al. 2006). These two processes result in an immediate carbon loss from the forest following fire, with a slow recovery of carbon as NEP increases over a period of decades. The assessment of postfire carbon dynamics in boreal forests is being actively studied by several groups of researchers to address both the current role of fire and the implications of changes to fire regimes in the future. These studies include the measurement of direct carbon exchange between the for-

Received 11 February 2008. Accepted 6 October 2008. Published on the NRC Research Press Web site at cjfr.nrc.ca on 7 February 2009.

B. Amiro.[1] Department of Soil Science, University of Manitoba, Winnipeg, MB R3T 2N2, Canada.
A. Cantin, M. Flannigan, and W. deGroot. Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, ON P6A 2E5, Canada.

[1]Corresponding author (e-mail: brian_amiro@umanitoba.ca).

est and the atmosphere from flux towers (e.g., Amiro 2001; Goulden et al. 2006) and the use of carbon inventories along chronosequences (Wang et al. 2003; Bond-Lamberty et al. 2007). The challenges are to understand the role of site-specific factors and the successional development of vegetation, which can both be highly variable, even in a small geographic area. Another factor that must be taken into account is interannual variability, which is driven by fluctuations in weather conditions (Chen et al. 1999; Barr et al. 2002). The uncertainty is still relatively large in our ability to integrate across large forest areas for any short time period. Also, inventory methods that integrate over large areas and longer times indicate that postfire dynamics are very important (Kurz and Apps 1999). Hence both combustion and postfire dynamics must be considered in a full assessment of the impact of fire on the carbon balance. In addition, the fire regime dictates the state of the forest ecosystem, including stand age structure and carbon pools. These system feedbacks between fire and forest development control both the carbon available for combustion and the fuels that determine fire behaviour.

Several assessments have estimated the direct combustion emissions from forest fire in boreal regions. These have been done for Alaska (French et al. 2003), Siberia (Kajii et al. 2002; Soja et al. 2004), and the whole boreal region (Kasischke et al. 2005; Balshi et al. 2007). Many assessments use remote sensing techniques to estimate the area burned in a given period, whereas some use mapping data from fire agencies based on a variety of mapping methods. In either case, the area-burned estimates are combined with an estimate of fuel consumption to calculate total emissions from a region. There are basically two techniques commonly used to calculate fuel consumption density (kilograms of dry fuel per square metre). The first of these is to estimate the fraction of fuel that is normally consumed during a fire in a region, based on measurements of a population of fires, combined with knowledge of available fuel. This technique has been widely used in estimates for Alaska (French et al. 2003) and Siberia (Soja et al. 2004), and a thorough discussion is provided by Kasischke and Penner (2004). This method requires a good knowledge of both available fuel inventory and fractional losses. In principle, it does not consider fire weather, which is known to directly determine the depth of burn of a fire (Forestry Canada Fire Danger Group 1992). However, the fractional fuel consumption is sometimes adjusted based on fire severity (Kasischke and Bruhwiler 2003), which provides some qualitative input based on weather.

An alternative approach is to include information about fire weather to directly estimate fuel consumption. Previously, Amiro et al. (2001) used the Canadian Forest Fire Behaviour Prediction System (FBP, Forestry Canada Fire Danger Group 1992) to estimate fuel consumption from Canadian fires for 1959–1995. This system estimates fuel consumption density based on relationships that have been developed between fire weather and the fuel consumed during both experimental fires and wildfires. Decades of observations by scientists and fire management personnel have established that the depth of burn depends on the dryness of the surface fuels. In particular, it is possible to have large fires in the spring without them burning deeply, whereas late summer fires are generally more severe (deeper burning). For most Canadian fuel types, the relationship between weather and fuel consumption can be estimated using component values of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). This includes the Buildup Index, which is an indicator of the amount of fuel available for combustion by a moving flame front. This index is a combination of the Duff Moisture Code and the Drought Code, which are indicators of the moisture content of loosely compacted surface organic material and deeply compacted organic layers, respectively. In particular, the Drought Code has a distinct drying trend through the season (Amiro et al. 2004), demonstrating that weather needs to be taken into account to estimate emissions. This approach has also been used recently by Turquety et al. (2007).

Peatland fires also show significant correlation with components of the FWI System, especially the Duff Moisture Code and the Drought Code (Turetsky et al. 2004). This relationship supports the concept that the dryness of the fuel partly dictates the amount of consumption. Although there may be upland areas where fire can be sufficiently severe to consume all organic material, these areas mostly occur on thin soils, often on the boreal and taiga shield. In most areas, the depth of burn is limited by deeper moist fuels or by a lack of oxygen for combustion.

The evidence that fire weather influences fuel consumption density in Canadian boreal fires is strong, with fire management strategies and prescriptions for prescribed fires incorporating fire weather parameters. A concern that follows from this relationship is the potential for a warmer and drier climate to increase fuel consumption in the future. Flannigan et al. (2005) estimated that the area burned in Canada could potentially double in a $3\times CO_2$ environment, a condition that is likely to occur by about 2100 (Solomon et al. 2007). In addition, the fire season may lengthen, increasing the period during which fires occur (Wotton and Flannigan 1993). In the current paper, we evaluate the potential effects of climate change on forest floor fuel consumption by forest fires. This is done by incorporating our best knowledge on changes in area burned and on forest floor fuel consumption density. The objective is to provide projections that can be used to understand some climate feedbacks that may increase atmospheric loading of gases and particulate matter. Findings that indicate an increase in greenhouse gases will have global implications because of the large area burned in Canada.

Methods

Estimates of future area burned

We work on an ecozone basis (Fig. 1), as has been done in previous analyses of fire in Canada (Amiro et al. 2001; Stocks et al. 2002; Flannigan et al. 2005). This approach allows regional comparisons that are used to differentiate current from future climate and to determine the role of landscape features. We focus on ecozones representing much of the Canadian boreal and taiga regions where fire is prevalent. These are the Taiga Plains, Taiga Shield, Boreal Shield, and Boreal Plains ecozones. As in previous analyses, we have split the Boreal Shield and Taiga Shield ecozones into east and west regions because of differences in fuel

Fig. 1. Location of the six ecozones used in the present study. The cordilleran ecozones in the west are excluded because of the uncertainty of the global climate model in mountainous areas, and the ecozone south of Hudson Bay is excluded because of the small number of weather stations.

types and fire occurrence (Amiro et al. 2001). These ecozones represented 88% of the area burned in Canada from 1959 to 1997 (Stocks et al. 2002).

Flannigan et al. (2005) used data from daily runs from the Canadian and Hadley Centre Global Climate Models (GCMs) to project future area burned for Canada. They found that monthly averaging gave the best regressions between the estimate of area burned for the GCM and the actual area burned for the 1959–1997 period. The regressions were based on a mixture of between one and four fire weather variables, including mean air temperature, maximum air temperature, total precipitation, minimum relative humidity, Fine Fuel Moisture Code, maximum Fine Fuel Moisture Code, Duff Moisture Code, maximum Duff Moisture Code, Drought Code, Initial Spread Index, daily severity rating, and Fire Weather Index. The strength of these relationships depended on the ecozone. The regressions were significant, with between 36% and 64% of the variance in area burned explained. We used the approach developed by Flannigan et al. (2005) to derive equations relating monthly area burned to weather and fuel moisture indexes using stepwise regression (SAS Institute Inc. 2000). Table 1 shows the equations by ecozone. The equations are slightly different from those used in Flannigan et al. (2005) because the study areas were different and the period used in this study was longer (1959–1999). These relationships were used to estimate area burned for three scenarios, all using the Canadian GCM version CGCM1. The model includes both greenhouse gas and sulphate aerosol forcing and has a grid spacing of about 3.75° latitude by 3.75° longitude. The $1\times CO_2$ scenario was based on the 1975–1995 period, inclusive. The $2\times CO_2$ and $3\times CO_2$ scenarios represent model outputs for the 2040–2060 and 2080–2100 periods, respectively. Daily noon meteorological variables were used, and temperature and precipitation were adjusted according to the procedure outlined by Flannigan et al. (2005).

Fuel consumption density

The FBP System model gives estimates of daily fuel consumption for Canadian fires based on regression relationships with fire weather variables (Forestry Canada Fire Danger Group 1992). These relationships were developed for each of the FBP fuel types, based on a population of prescribed fires. Previously, Amiro et al. (2001) used the FBP System to calculate the daily fuel consumption for Canadian fires in the 1959–1995 period for each ecozone. However, additional data have been collected on Canadian fires since the development of the FBP System models, especially on wildfires that occurred after extended drying periods. de Groot et al. (2009) reanalysed the previous data sets with the additional data and developed a relationship that is independent of fuel type. This relationship only estimates forest floor fuel consumption, which would likely be more affected by a change in soil moisture than would be crown fuel consumption in a future climate. The relationship was derived from data at 128 sites representing six large experimental burning projects and seven large wildfires in Ontario, Manitoba, Saskatchewan, Alberta, the Northwest Territories, and the Yukon. Mean forest floor consumption ranged from 0.1 to 3.9 kg dry fuel·m^{-2}. Combining all the data, de Groot et al. (2009) could explain 50% of the variance using the following equation:

Table 1. Equations used to estimate monthly ecozone area burned (ha).

Ecozone	Equation	R^2
Taiga Plains	exp(1.234 mdsr + 0.512mtemp – 3.469)	0.57
Taiga Shield west	exp(0.0372 xdmc + 0.311mtemp + 0.368xtemp – 8.691)	0.58
Taiga Shield east	exp(0.142xbui + 0.357xtemp – 5.458)	0.35
Boreal Shield west	exp(1.032xffmc + 0.055xdmc + 0.405mtemp – 93.944)	0.58
Boreal Shield east	exp(0.271xdmc – 0.402)	0.30
Boreal Plains	exp(1.022xffmc + 0.129mdmc – 0.029tprec – 88.810)	0.50

Note: All R^2 values are significant at $P < 0.01$. The variables (unitless unless specified) are mtemp, monthly mean air temperature (°C); xtemp, monthly maximum air temperature (°C); mdmc, monthly mean Duff Moisture Code; xdmc, monthly maximum Duff Moisture Code; xbui, monthly maximum Buildup Index; xffmc, monthly maximum Fine Fuel Moisture Code; mdsr, monthly mean daily severity rating; tprec, monthly total precipitation (mm).

$$[1] \qquad C = 1.185 \exp\left(-4.252 + 0.671 \ln F + 0.71 \ln D\right)$$

where C is surface fuel consumption density (kilograms dry fuel per square metre), F is the fuel load (kilograms dry fuel per square metre), and D is the Drought Code from the FWI System (Van Wagner 1987). If the wildfires were excluded, the R^2 value increased to 0.72 because of the greater scatter among wildfire data at the higher Drought Codes. This scatter is probably partially caused by an inability to obtain prefire data that accurately reflects the conditions before the wildfires, although some of the variability is likely real. To solve eq. 1, we derived the Drought Code at noon daily for each scenario following Flannigan et al. (2005) and used this estimate as a mean value for each ecozone. This value is a spatial mean of the grid cells for the GCM. Monthly means of the daily values were used to derive eq. 1 for each month from May to August. Although fires also occur outside of this period, this captures most of the fire season in Canada (Stocks et al. 2002).

The fuel load term in eq. 1 is difficult to estimate. First, we need to set the fuel load to estimate the correct amount of forest floor fuel consumption. Second, we will assume that the fuel load does not change with a changing climate. Changes in forest fuels could occur with changes in forest type, differences in biomass accumulation, or changes in forest fire frequency and severity. The no-change assumption is likely not true, but it allows us to investigate the effect of changes in fire weather, independent of changes in forest fuels. de Groot et al. (2009) report mean fuel loads for each of the FBP fuel types. We used these mean fuel loads and the fraction of each fuel type in an ecozone (Amiro et al. 2001) to estimate an ecozone mean surface fuel load (Table 2). Fuel type clearly determines the ecozone fuel load, with mean values ranging from 1.8 $kg{\cdot}m^{-2}$ in the Taiga Shield west to 6 $kg{\cdot}m^{-2}$ in the Boreal Shield east.

Fire weather

Equation 1 requires an estimate of the Drought Code. The Drought Code represents the moisture content of larger and deeper fuels with a time constant of 52 days (Van Wagner 1987). Hence it reflects the ability of fires to burn deeply into organic soil and consume coarse woody debris. For both the weather database and the GCM calculations, the Drought Code was set to a value of 15 at the start of the fire season, which is the standard value. However, note that this value could be greater if very dry conditions persist over winter. We do not have sufficient knowledge to estimate the additional impact of climate change on this overwintering effect and therefore use a constant spring initial value for each scenario.

The GCM was run on a daily time step to estimate fire weather within each ecozone, based on the average weather for the 21 year period for each scenario. The Drought Code was calculated as a monthly mean, which includes all conditions, including periods when wet conditions prevailed and fires were likely not burning. Hence, the GCM-derived Drought Code would underestimate the conditions when fires were burning. Recognizing this limitation, we calculated the measured monthly mean Drought Code for the 1975–1995 period based on the weather that occurred with each fire recorded in the large-fire database (Stocks et al. 2002) for each ecozone. These fire weather variables represent the actual conditions when fires were burning and are a subset of the statistics presented by Amiro et al. (2004). We then adjusted the GCM values using the relationship between the fire database records and the $1{\times}CO_2$ scenario, with a regression equation.

Total forest floor fuel consumption

The total monthly forest floor fuel consumption was calculated for each ecozone as the product of the forest floor fuel consumption density and the area burned for that ecozone (kilograms of dry fuel per month). This weighted the consumption by the area burned. Annual totals were then constructed as the sum for the four months (May to August). Summing across the annual totals for all ecozones gives an approximation of the total fuel consumed by Canadian fires. Previously, Amiro et al. (2001) did this for 15 ecozones, including two ecozones that were split into east and west sections. In the present study, we had insufficient information to apply the GCM to several of these ecozones because of either complex terrain or the small size of the ecozone. In addition, we have excluded the Hudson Plains ecozone because the very small number of weather stations limits our ability to estimate historical fire weather needed to scale the GCM estimates. Hence, we could only evaluate the Taiga Plains, Taiga Shield east and west, Boreal Shield east and west, and Boreal Plains. These ecozones represent 86% of the total emissions for Canada during the 1959–1999 period (Amiro et al. 2001).

Table 2. Surface fuel loads to estimate forest floor fuel consumption.

Ecozone	Fraction of fuel type in each ecozone C1	C2	C3	C4	D	M	Mean fuel load for ecozone ($kg\cdot m^{-2}$)
Taiga Plains	0.28	0.35	0.01	0.01	0.13	0.21	5.13
Taiga Shield west	0.91	0.02	0.02	0.01		0.03	1.81
Taiga Shield east	0.71	0.28					3.44
Boreal Shield west	0.04	0.48	0.21	0.09	0.06	0.13	5.81
Boreal Shield east	0.12	0.50	0.04	0.02	0.16	0.17	6.02
Boreal Plains		0.24	0.14	0.06	0.39	0.17	4.99
Fuel type load ($kg\cdot m^{-2}$)	1.5	8.3	3.3	1.3	3.9	5.7	

Note: Fuel types are as follows: C1, spruce–lichen woodland; C2, boreal spruce; C3, mature jack or lodgepole pine; C4, immature jack or lodgepole pine; D, deciduous; M, mixedwood. The fuel types are defined by Forestry Canada Fire Danger Group (1992), with "C" indicating a coniferous type, "D" indicating deciduous broadleaf type, and "M" indicating a mixed canopy with a coniferous component varying between 25% and 75%. The fraction of fuel types in each ecozone is taken from Amiro et al. (2001), whereas the fuel load for each fuel type is from de Groot et al. (2009). Note that some fractions may not add to unity because of rounding.

Emission factors for gases and particles

Estimates of total surface fuel consumption provide the basis for estimating emissions of gases and particles because these are usually based on the amount of fuel consumed. Hence the flux of compound i emitted by fires (M_i, grams per square metre) is calculated as

$$[2] \qquad M_i = E_i C$$

where E_i is the emission factor for compound i (grams of compound per kilogram of dry fuel). Some of the best measurements of these gases and particles have been obtained from Canadian fires (e.g., Cofer et al. 1990, 1998; Conny and Slater 2002). Based on these data and additional information, Andreae and Merlet (2001) compiled an exhaustive list of emission factors from fires for a variety of gases and particles. We use their database for extratropical forests as an approximate indicator of the atmospheric loading of some important compounds. We specifically focus on the emissions of the following (associated mean values for E_i provided in parentheses): CO_2 (1569), CO (107), CH_4 (4.7), total non-methane hydrocarbons (5.7), NO_x (3.0), N_2O (0.26), $PM_{2.5}$ (13), and total particulate matter (17.6).

Results

Area burned

We estimate that the area burned over the six major ecozones will increase by about one-third in a $2\times CO_2$ scenario and double in a $3\times CO_2$ scenario (Table 3). These ecozones cover most of the northern forest area in Canada that experiences large fires. The estimates vary slightly among the ecozones, with the Boreal Shield west and Taiga Shield west having the greatest percent increases and the Taiga Plains, the smallest increase. Through all scenarios, the Boreal Shield west exhibits the greatest area burned.

This increase in area burned is weighted more towards May and June, especially in the $3\times CO_2$ scenario (Fig. 2). This estimated change in seasonality indicates that the area burned in May will equal that burned in August in the $3\times CO_2$ environment, whereas May currently accounts for

Table 3. Annual mean area burned (km^2) by fires greater than 2 km^2 in size for each ecozone.

Ecozone	$1\times CO_2$	$2\times CO_2$	$3\times CO_2$
Taiga Plains	5 674	6 213	6 916
Taiga Shield west	3 575	6 355	8 671
Taiga Shield east	1 731	2 054	3 344
Boreal Shield west	6 814	9 550	17 478
Boreal Shield east	1 367	1 338	1 905
Boreal Plains	3 119	4 391	4 755
Total	22 279	29 901	43 068

Note: The area burned for the $1\times CO_2$ scenario is identical to the actual recorded area burned for the 1975–1995 period inclusive.

much less of the area burned yearly. For all scenarios, June has the greatest area burned.

Fuel consumption density

The GCM calculates monthly mean Drought Code values that reflect all conditions, even when it is too wet for fires to burn. We calculated the mean monthly Drought Code measured at weather stations within each ecozone during periods when fires were burning based on the data set of Amiro et al. (2004) but for the 1975–1995 period only. These values were clearly related (R^2 = 0.96) with the GCM values for the $1\times CO_2$ scenario (Fig. 3). Hence, we adjusted the GCM values for all three scenarios using the regression presented in Fig. 3. The assumption is that the changes in the Drought Code for future scenarios would not exceed the dynamic range of the regression, and that this relationship would hold for all climates for these specific ecozones. Neither the Hudson Plains nor Boreal Cordillera ecozone followed this relationship for reasons given previously, and we do not expect that this regression is easily transferable to other ecozones.

For most ecozones, the forest floor fuel consumption density increases in the future scenarios by a few percent (Table 4). The maximum percent increase is for the Boreal Shield East ecozone, which shows an 18% increase in the

Fig. 2. Monthly estimates of area burned in the six ecozones for three climate scenarios.

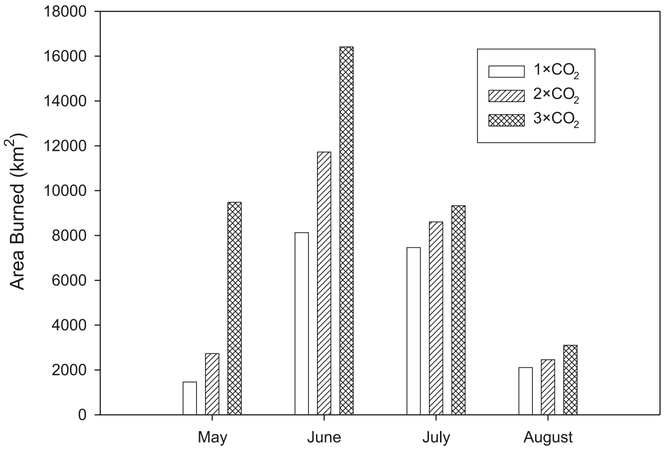
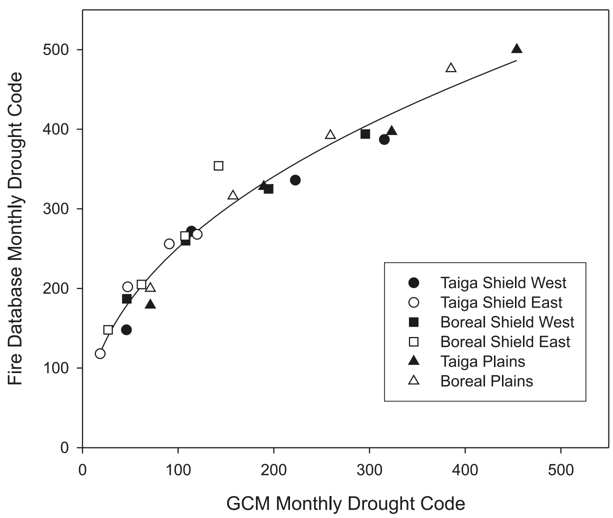


Fig. 3. Relationship between monthly Drought Code from the fire database and the GCM $1\times CO_2$ scenario for May to August, inclusive. The line is a regression with $y = 35.68x^{0.429} - 5.96$ ($R^2 = 0.96$).



$3\times CO_2$ scenario compared with the $1\times CO_2$ scenario. The Boreal Shield west ecozone shows no net change over the three scenarios. These changes are all caused by a change in the Drought Code, because the fuel load has been kept constant. Hence, conditions are projected to be slightly drier overall. The estimates were made as a monthly mean, and it is instructive to examine the changes and trends monthly. Figure 4 illustrates that the fuel consumption density increases from May to August in all ecozones, following the progression of the Drought Code (see Amiro et al. (2004) for seasonal trends in the Drought Code of Canadian fires). This progression is typically about a doubling of fuel consumption density in August compared with May. Further, the differences in fuel consumption density among the climate change scenarios are small compared with the seasonal variability. This demonstrates that fires late in the season have a much greater impact on emissions and fuel loss than early-season fires.

Table 4 also compares forest floor fuel consumption density between the new fuel consumption model and that used previously by Amiro et al. (2001). The Taiga Shield ecozones give slightly lower values using the new model, but the other four ecozones give higher values. Overall, the new model produces higher fuel consumption values for the $1\times CO_2$ scenario as well as for current conditions in Canada.

Total fuel consumption

The full impact of emissions is estimated as the product of the fuel consumption density and the area burned in each month, then totalled for the four months (Table 5). The overall increase in forest floor fuel consumption for the six ecozones is 34% for the $2\times CO_2$ and 94% for the $3\times CO_2$ scenarios. These percent increases are essentially the same as those obtained for the area burned (Table 3) because of the small effect on fuel consumption density (Table 4). Table 5 also reports a previous estimate by Amiro et al. (2001) for the same ecozones that includes both surface and crown fuel consumption, averaged over the 1959–1995 period. The use of the new fuel consumption model clearly leads to higher surface fuel consumption values compared with the method of Amiro et al. (2001).

Emissions of gases and particles

The estimates of fuel consumption from each ecozone allow us to estimate emissions of several constituents of atmospheric interest (Table 6). These totals are only for the six ecozones, but likely represent about 86% of the emissions from Canadian fires (Amiro et al. 2001). The amount of CO_2 emitted is estimated to increase from about 95 Tg·year^{-1} in the $1\times CO_2$ scenario to 183 Tg·year^{-1} in the $3\times CO_2$ scenario. The emission factor for CO_2 used here scales to about 0.43 kg C·(kg dry fuel)$^{-1}$, which is slightly less than the carbon fraction of 0.5 kg C·(kg dry biomass)$^{-1}$ that is often used for a carbon loss fraction from fire (e.g., Kurz and Apps 1999; Amiro et al. 2001). Carbon monoxide emissions are about 7% of the CO_2 emissions, but the relative amount of CO depends on the mix of flaming and smouldering combustion (e.g., Cofer et al. 1998). Although methane and non-methane hydrocarbon emissions are less than carbon oxide emissions, together these compounds release 1 Tg·year^{-1} in the $3\times CO_2$ scenario. The methane molar CO_2 equivalent warming potential over a 100 year period is greater by a factor of about 25 than the warming potential for CO_2 (Forster et al. 2007), so that the contribution of methane to the greenhouse gas mass equivalent will be about 20% of that of CO_2.

Oxides of nitrogen are also important. Nitrous oxide, in particular, could be released at 30 Gg·year^{-1} in the $3\times CO_2$ scenario, and with a molar equivalent to CO_2 of about 298 (Forster et al. 2007), it will be about 5% of the greenhouse gas mass equivalent of CO_2. Total particulate matter loading is about 2 Tg·year^{-1} for the $3\times CO_2$ scenario, with about 75% of this particle matter less than 2.5 μm in size.

Uncertainty and sensitivity

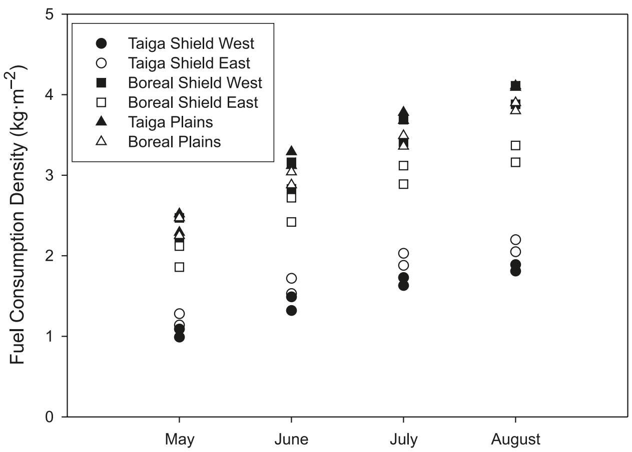
Most of the increase in fuel consumption with climate change is expected to be caused by a change in the area burned (Table 3), with much less resulting from changes in fuel consumption density (Table 4). Hence, the uncertainty in area burned will have a greater impact on estimates of fire emissions. Our best estimate of uncertainty is likely based on a comparison among different GCMs. Flannigan et

Table 4. Mean forest floor fuel consumption density by ecozone (kg dry fuel·m^{-2}) for May to August, weighted by area burned in each month.

Ecozone	Amiro et al. 2001	$1\times CO_2$	$2\times CO_2$	$3\times CO_2$
Taiga Plains	2.52	3.46	3.51	3.54
Taiga Shield west	1.66	1.46	1.53	1.61
Taiga Shield east	1.78	1.72	1.79	1.94
Boreal Shield west	2.06	3.01	3.08	2.99
Boreal Shield east	1.79	2.40	2.52	2.71
Boreal Plains	2.03	2.78	2.84	3.04

Note: The values from Amiro et al. (2001) are the mean values from weather for each fire greater than 200 ha in size during the 1975–1995 period using the Canadian Forest Fire Behaviour Prediction System fuel consumption equations.

Fig. 4. Monthly mean forest floor fuel consumption density. For each ecozone, identical symbols are used for the $1\times CO_2$ and $3\times CO_2$ scenarios, with the higher value being for the $3\times CO_2$ scenario.



al. (2005) compared results for area burned for different ecozones using both the Canadian and Hadley GCMs. The Hadley GCM estimated a 27% greater area burned than the Canadian GCM for the $3\times CO_2$ scenario for the six ecozones used in the present paper. Although this result does not give us a true measure of uncertainty, it does indicate the magnitude with which GCMs vary when estimating area-burned projections. It is also important to note that our regressions for area burned only account for 30% to 58% of the variability (Table 1).

Fuel consumption density is assumed to be a function of the Drought Code and fuel load (eq. 1) based on a recent reanalysis of the Canadian fire data (de Groot et al. 2009). This model is clearly different from the previous model used by Amiro et al. (2001), which was dependent on fuel type and the Buildup Index, both components of the FBP system. The Buildup Index incorporates both the Drought Code and the Duff Moisture Code, so there is some relationship between the two models. We have uncertainty in the applicability of any fuel consumption model to general wildfires in Canada because of the large variability among fires and only limited data sets where measurements have been taken. The model of de Groot et al. (2009) explained 50% of the variation among all fires in the data set, although it did much better for the experimental fires alone. We also needed to scale the GCM-derived Drought Code to the Drought Code that occurs during fires (Fig. 3). The regression for this relationship had R^2 = 0.96, suggesting that we know this within about 4%.

It is difficult to estimate fuel loads over a broad geographical area such as an ecozone. Our method used the fuel classification estimates from Amiro et al. (2001), which were based on forest inventory data. The fuel load was then based on a mean load for each type, weighted by the fractional coverage of each fuel type. de Groot et al. (2009) give standard deviations for the fuel loads used in the derivation of the fuel consumption equation. The coefficient of variation (CV) ranges from 15% for the C4 (immature pine) fuel type to 48% for the C3 (mature pine) fuel type. The C2 (boreal spruce) fuel type had a CV of 42%. This fuel type is likely the most indicative of the overall uncertainty because of its prevalence in ecozones that have large burned areas (Tables 2, 3). Hence we assume that the uncertainty in the fuel load is 42% and that the fuel classification does not add additional uncertainty. It is important to note that this uncertainty is based on variability among sites, and it is likely that the uncertainty in a broad ecozone average of all fires could be much less because of spatial averaging.

We estimate the overall uncertainty based on the errors of 27% for area burned (±11 628 km^2), 50% for the fuel consumption equation, 4% for Drought Code adjustment, and 42% for the fuel load uncertainty as the CV. As an example, if all parameters are varied by their range of uncertainty, the sum for the $3\times CO_2$ scenario for the six ecozones yields a change in total fuel consumption from 117 Tg dry fuel (Table 5) to as high as 289 Tg dry fuel (+150%) or as low as 47 Tg dry fuel (–60%).

Andreae and Merlet (2001) report uncertainties for emission factors (Table 6). These range from about 8% for CO_2 to 80% for non-methane hydrocarbons. The total emissions scale with the emission factors so that these additional uncertainties need to be added to the uncertainty in fuel combustion and area burned to evaluate the overall emission uncertainty. Also note that the linear scaling allows for a transparent conversion if alternate emission factors are used.

Discussion

Estimates of fuel consumption from Canadian fires

In a previous assessment, Amiro et al. (2001) used the FBP system to estimate fuel consumption for Canadian ecozones. This system calculates fuel consumption based on fire weather with equations that are dependent on fuel type. This approach is different from alternative approaches that estimate fuel consumption as a constant fraction of available fuel (e.g., Wiedinmyer et al. 2006). In these other calculations, weather is not a variable, implying that the depth of fire burn does not change with fuel moisture conditions. Such a constant fractional assumption also implies that a changing climate will not change fuel consumption, except if there are climate-related changes to the fuel loading. The reanalysis by de Groot et al. (2009) indicates that both weather (through the Drought Code) and fuel load are important. However, the predictive accuracy of the model decreased at higher fuel consumption values because of variability in the wildfire data set. This variability imposes

Table 5. Mean annual total ecozone forest floor fuel consumption (Gg dry fuel per ecozone).

Ecozone	Amiro et al. 2001	$1\times CO_2$	$2\times CO_2$	$3\times CO_2$
Taiga Plains	11 474	19 620	21 802	24 461
Taiga Shield west	5 292	5 235	9 702	13 991
Taiga Shield east	2 556	2 974	3 679	6 479
Boreal Shield west	14 122	20 481	29 426	52 277
Boreal Shield east	5 282	3 279	3 377	5 170
Boreal plains	6 888	8 683	12 482	14 437
Total	45 614	6 0271	80 467	116 815

Note: The data from Amiro et al. (2001) are for the 1959–1995 period for both surface and crown fuel combustion, for comparison.

additional uncertainty and is likely caused by a mixture of real variability among fires, our ability to properly characterize fuel consumption for wildfires, and our ability to estimate fire weather conditions at wildfires after they have occurred. The evidence from prescribed fires is more reliable, but it is difficult to conduct experimental burns under extreme fire weather conditions similar to those that prevail during wildfires. The variability suggests that it might be very difficult to observe a climate change impact on fuel consumption density, negating even the very small percent change calculated using the model and the GCM weather projections. This would mean that most of the change in emissions will come from changes in area burned.

Figure 5 illustrates the relative contributions of weather and fuel over the mean range of Drought Code values for each ecozone with the different mean fuel loads for each ecozone. This comparison shows that the seasonal change in Drought Code from May to August has about a twofold effect on fuel consumption for any given fuel loading. However, it also shows that the fuel load effect among the different ecozones is also about a twofold effect at similar Drought Code values. The conclusion is that both fuel load and weather are about equally important for estimating fuel consumption with some confidence. This finding is supported by anecdotal information from forest fire management personnel, who commonly evaluate the potential depth of burn based on both the available fuel and the Drought Code. This knowledge is used to estimate the difficulty of extinguishing surface fires in wildfire and prescribed fire situations. It is important to note that we have used the default algorithm for the Drought Code, which resets the values to 15 at the start of the spring fire season. Under very dry spring conditions, fuel consumption could be higher than we have estimated.

Tables 2 and 4 also provide information for calculating fractional forest floor fuel consumption for comparison with other studies. The mean fractional consumption for all ecozones is 0.57 for the $1\times CO_2$ and 0.62 for the $3\times CO_2$ scenarios. However, individual ecozones vary from less than 0.4 to greater than 0.8. Recently, Balshi et al. (2007) estimated carbon losses from fire across the boreal region of North America and Eurasia. They used the fractional estimates of French et al. (2000) for Canadian ecozones. These estimates have separate aboveground and ground-layer fractions and densities, and the fractional loss is therefore not easily convertible to the fuel loads given in Table 2. However we can compare our fuel consumption density values with those of French et al. (2000) , which are 2.92 kg·m^{-2} for Taiga Plains, 0.97 kg·m^{-2} for Taiga Shield west, 1.55 kg·m^{-2} for Taiga Shield east, 2.09 kg·m^{-2} for Boreal Shield west, 2.59 kg·m^{-2} for Boreal Shield east, and 3.79 kg·m^{-2} for Boreal Plains. With the exception of the Boreal Shield east, the values presented here are all slightly greater than those of French et al. (2000), but the mean ecozone difference is only 6%.

We reanalysed the data of Amiro et al. (2001) to estimate forest floor fuel consumption density for the 1975–1995 period for the six ecozones. This analysis gave a mean fuel consumption density of 2.02 kg·m^{-2}, which is about 75% of the mean value of 2.7 kg·m^{-2} estimated using the de Groot et al. (2009) model. Turquety et al. (2007) estimated boreal fire fuel consumption for 2004 using the Amiro et al. (2001) method but increased the total fuel consumption density by 50% of the standard deviation, which is about an additional 0.5 kg·m^{-2}. The new model would suggest that this might still be an underestimate, especially if we add about an additional 0.3 kg·m^{-2} as crown fuel consumption (Amiro et al. 2001).

In addition to the estimated uncertainties, potential bias is important to consider. The comparison of Flannigan et al. (2005) for projected area burned between only two GCMs indicates that the Canadian GCM is biased towards a lesser area burned compared with the Hadley model. The area burned was correlated with fire weather, and we could extend this comparison to suggest that the Canadian GCM might also bias the Drought Code to lower values. The implications are that we may be underestimating the fuel consumption and emissions for future scenarios. The current study only reports consumption and emissions for the boreal and taiga ecozones in Canada. If we assume that our new values scale nationally with the relative distribution reported by Amiro et al. (2001), these boreal and taiga ecozones account for about 86% of the total emissions from all Canadian forests. In addition, the surface fuel consumption is about 85% of the total fuel consumption, once the crown fuel component is added. Hence, the total Canadian forest fire fuel consumption and emissions can be estimated by increasing the sum of the six ecozone values by 36% (i.e., 18% for the crown fuel component compounded by 16% for the additional ecozones). We have shown this in Table 6 as our best overall estimate of greenhouse gas emissions.

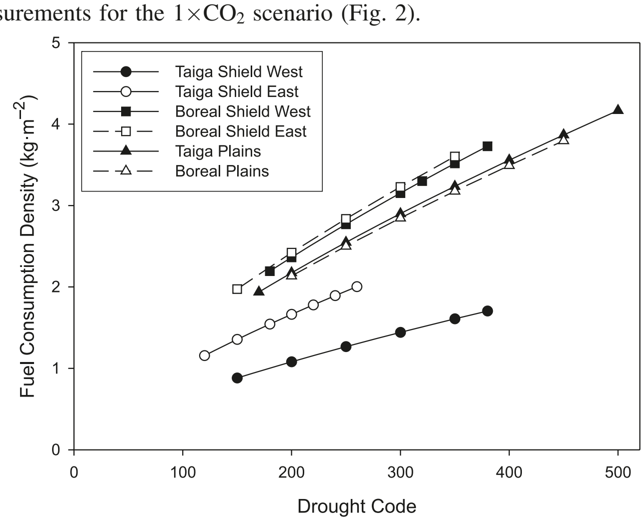
Our values represent the general forest but are likely biased towards upland sites. Turetsky et al. (2004) concluded that fires do not burn preferentially in upland areas compared with bogs and fens in central Alberta. In addition, large fires tend to burn a greater percentage of peatlands (Flannigan et al. 2008). The area-burned estimates do include peatlands, since they were developed from observations of fire size for the whole landscape. However, we need to evaluate whether our ecozone mean estimates of fuel consumption density also include peatlands. Turetsky and Wieder (2001) and Turetsky et al. (2002) estimate that peatland fuel consumption densities can be greater than 6 kg dry fuel·m^{-2} but averages over large areas of western Canada are typically in the range of 0.4 to 2.4 kg·m^{-2} (Turetsky et al. 2006). This rate is similar to our ecozone mean values shown in Table 4. The use of the Drought Code as the weather indicator likely works

Table 6. Emissions of gases and particles from the six ecozones (Gg·year^{-1}).

Constituent	Emission factor (g·(kg dry fuel)$^{-1}$)	1×CO_2	2×CO_2	3×CO_2
Carbon dioxide (CO_2)	1569±131	94 565	126 253	183 283
Carbon monoxide (CO)	107±37	6 449	8 610	12 499
Methane (CH_4)	4.7±1.9	283	378	549
Total non-methane hydrocarbons	5.7±4.6	344	459	666
Nitrogen oxides excluding N_2O	3±1.4	181	241	350
Nitrous oxide (N_2O)	0.26±0.07	16	21	30
Particle matter <2.5 µm	13±7.0	784	1 046	1 519
Total particulate matter	17.6±6.4	1 061	1 416	2 056
Black carbon	0.56±0.19	34	45	65
CO_2 equivalent for CO_2, CH_4, N_2O forest floor boreal ecozones		118 809	158 466	229 953
CO_2 equivalent including crown fuel for all Canada		161 580	215 514	312 736

Note: The emission factors are from Andreae and Merlet (2001) for extratropical forests. Calculation of CO_2 equivalent uses a 100 year time horizon (Forster et al. 2007). Canada-wide totals (last row) include a 36% increase to account for non-boreal fires and crown fuels.

Fig. 5. Relative effects of weather (Drought Code) on fuel consumption density. The ecozones have fuel load values (kg dry fuel·m^{-2}) of 5.13 for Taiga Plains, 1.81 for Taiga Shield west, 3.44 for Taiga Shield east, 5.81 for Boreal Shield west, 6.02 for Boreal Shield east, and 4.99 for Boreal Plains. The range of Drought Code values corresponds to the monthly means from the weather measurements for the 1×CO_2 scenario (Fig. 2).



well for estimating depth of burn in peatlands. In particular, spring fires with low Drought Codes will not burn deeply, so that fuel consumption in the peatland is likely similar to that in upland areas. Alternatively, high water tables in peatlands in spring reduce the area of dry fuel. However, in late summer, deep burning fires would be expected with fuel consumption density greater than the ecozone mean. In the worst cases, these fires could smoulder over winter and burn again in spring. These deep-burning fires can be a great concern, not only because of the amount of carbon that is lost from the ecosystem, but also because of the emission of mercury that has accumulated in the peat (Turetsky et al. 2006).

We used emission factors from Andreae and Merlet (2001) as the single compendium for greenhouse gases and other constituents. These values are based on the general literature and may not be the best estimates for specific Canadian boreal fires. For example, the carbon content of fuels reported by de Groot et al. (2009) for Canadian wildfires range from 0.41 to 0.54 kg C·(kg dry biomass)$^{-1}$, with the best overall estimate being about 0.48 kg C·(kg dry biomass)$^{-1}$. This estimate is slightly greater than the value of 0.43 kg C·(kg dry biomass)$^{-1}$ derived from the Andreae and Merlet (2001) CO_2 emission factors. As mentioned previously, the emission factors for CO depend on the relative amounts of flaming and smouldering combustion, with smouldering combustion having about twice the CO emission factor of flaming combustion (Cofer et al. 1990). Although the ratio of smouldering to flaming combustion can be adjusted as a function of the depth of burn (Kasischke et al. 2005), the mean value from Andreae and Merlet (2001) is based on several studies of atmospheric sampling, so it includes a mixture of conditions measured over fires.

Impact of a changing fire regime on the forest

In this study, we have evaluated the potential effect of a changing climate on the area burned and the fuel consumption caused directly through drying of fuel. We have assumed that the fuel load does not change for the future scenarios. This assumption allows the evaluation of the direct climate impact alone, but likely overlooks changes to the forest that will occur over the next century. Changes in fuel load are very difficult to predict. Much of the assessments to date suggest that forest growth may increase with a changing climate but changes to the moisture balance also have important effects (Field et al. 2007). Our uncertainty is sufficiently great that it is more reasonable to maintain the assumption of no change in forest fuel load associated with changes in ecosystem production. However, an increase in area burned will change the fire cycle with likely implications for changes in the amount of fuel available for subsequent fires. Although there are data on the change in detrital material and fuel loads along boreal fire chronosequences (Wang et al. 2003), there is no information on changes to boreal fuel loads with a change in fire frequency. Fuel loads will possibly decrease if fires return to the same location at an increased frequency, although the amount of coarse woody debris is relatively constant after a few decades (Hely et al. 2000). With the $3\times CO_2$ scenario projected to occur on the scale of about one century, we could expect areas to burn more than once. An approximation of this effect would be that the fuel load decreases at the same rate as the area burned increases. This relationship would imply a potential for fuel loads in a $3\times CO_2$ scenario to be only 50% of those today. This amount is likely an overestimate because fuel load evolution is nonlinear, with the duff layer slowly developing and coarse woody debris peaking soon after the previous fire (e.g., Wang et al. 2003).

The effects of climate change on fuel consumption and carbon

We have only evaluated forest floor fuel consumption because we expect that it will be more affected by warmer and drier conditions than crown fuel consumption. The current Canadian crown fuel consumption model includes weather-determined variables, such as foliar moisture content, fire rate of spread, and forest floor fuel consumption (Forestry Canada Fire Danger Group 1992). In a warmer and drier climate, we would expect greater crown consumption, assuming no change to the forest canopy itself. However, a 10% increase in crown consumption will increase the total forest fuel consumption by less than 2% because the burning process is dominated by forest floor fuel consumption. If better forest canopy models are developed, we could investigate the additional role of crown fuel consumption in a changing climate, but the contribution of crown fuel consumption will still likely be less than our uncertainty in the forest floor fuel consumption estimates.

The future climate scenarios suggest that fuel consumption will increase overall by 34% in the $2\times CO_2$ scenario and 94% in the $3\times CO_2$ scenario. However, most of this increase is caused by an increase in the area burned. A recent analysis also suggests that the number of fire starts may increase with a changing climate, which could further increase the area burned (Krawchuk et al. 2009). The ability of fire management agencies to cope with these increases in fire activity is limited because these organizations operate with a narrow margin between success and failure, and a disproportionate number of fires may escape initial attack under a warmer climate. This situation could cause an increase in area burned that will be greater than the corresponding increase in fire weather severity, highlighting the need to search for the best estimates of area burned by fires in Canada. However, there could be some additional climate change impacts on fuel consumption density. A changing climate may alter forest hydrology, perhaps creating wetter landscapes in some areas and drier landscapes in others. There will likely be many forest management changes over the next century, some of these in response to a changing climate. In addition to fire suppression, management of insects and fuel (continuity, type, amount) could impact both area burned and fuel consumption density.

In the present analysis, we have only evaluated fires in the May to August part of the fire season. For boreal Canada, this period covers the majority of the current fires. A warming climate will likely extend the fire season into the spring and the fall (Wotton and Flannigan 1993), increasing the area burned and the fire emissions. Figure 2 shows that the area burned earlier in the season will likely increase, with May fires being a more important factor. Both the Drought Code and fuel consumption density are lower in the spring (Fig. 4), suggesting that this change will have a smaller effect than would an increase in late-season fires. In addition, earlier springs could also cause vegetation to become greener earlier, which would be a negative feedback (inhibiting fire) that is not considered in our estimates. We do not yet have estimates of the magnitude of this impact on emissions using the current generation of GCMs. However, the additional amount is likely within the upper bounds of the uncertainty.

Recently, Kurz et al. (2007) compared the possible disturbance effects with the potential increases in growth with a changing climate. The projected increases in area burned are more important than the potential enhanced growth, resulting in a net carbon loss from Canadian forests in the future.

Emissions of greenhouse gases and particles

The current CO_2 emission from the six ecozones is about 95 $Tg{\cdot}year^{-1}$ (Table 6), and if we scale this to include all Canadian forest fires plus the crown fuel component, we estimate that about 129 Tg CO_2 are released annually, on average. The global warming potential from methane and nitrous oxide over a 100 year horizon adds an additional 25% in CO_2 equivalent, with methane being about four times more important than nitrous oxide.

The anthropogenic emissions of greenhouse gases from Canadian sources in 2005 were about 747 $Tg{\cdot}year^{-1}$ of CO_2 equivalent (Environment Canada 2007). Under the $1\times CO_2$ scenario, we estimate greenhouse gas emissions from fires of about 162 $Tg{\cdot}year^{-1}$ of CO_2 equivalent, which represents about 22% of the anthropogenic emissions, on average. However, in the $3\times CO_2$ scenario, the fire contribution is estimated to increase to about 313 $Tg{\cdot}year^{-1}$ of CO_2 equivalent. Hence, the potential emissions from fire will be an important contribution to total emissions, especially if Canada's industrial greenhouse gas emissions are much lower by the time we reach a $3\times CO_2$ environment.

Randerson et al. (2006) have combined estimates of the radiative forcing properties of fires, including the emissions effects, as well as the postfire effects on surface albedo. They conclude that boreal fires could cause a net radiative cooling of $-2.3\ W{\cdot}m^{-2}$, with an uncertainty of $\pm 2.2\ W{\cdot}m^{-2}$. This net cooling is largely driven by an increase in the surface albedo following fires. For their calculations, Randerson et al. (2006) used a surface fuel consumption of $2.7\ kg{\cdot}m^{-2}$, including both the organic layer of the soil and plant understory. This value is in the same range as those calculated in our Table 4, and given the relatively small expected change in fuel consumption density in future climates, we could surmise that in the future, radiative forcing may not be much different than it is today on a per-area basis. If the estimates of Randerson et al. (2006) are correct, the projected increase in area burned could actually be a negative feedback to climate change. However, there is sufficient complexity in the earth–atmosphere system that such projections are difficult, and therefore we need to improve the detailed understanding of all mechanisms.

Conclusions

We have calculated new estimates for fuel consumption for the taiga and boreal ecozones of Canada. These estimates are slightly greater than the previous estimates and are based on both fuel loading and fire weather. This method has been applied using climate change scenarios for $2{\times}CO_2$ and $3{\times}CO_2$ environments, which are expected to be experienced in the twenty-first century. The area burned is projected to increase over time, eventually doubling by the $3{\times}CO_2$ case. There already appears to be a trend in increasing area burned over past decades that is correlated with a changing climate (Gillett et al. 2004). We also expect that fires will burn deeper and consume more fuel on an areal basis because of warmer and drier weather through much of the northern ecozones. However, the deeper-burning effect is relatively small, increasing fuel consumption by between 0% and 18%, depending on ecozone. Hence, changes in area burned have the greatest impact, doubling in the $3{\times}CO_2$ climate. These results suggest that fire management will continue to be important in the future to protect values at risk, human health, and ecological integrity. The net climate change effect is still uncertain when greenhouse gas emissions are balanced with radiative forcing caused by landscape change. However, the emissions of many other constituents, such as smoke (Begum et al. 2005), CO (Wotawa and Trainer 2000), mercury (Turetsky et al. 2006), and other compounds will likely increase in the future and may be the target for fire control in Canadian forests.

Acknowledgements

We thank the large number of colleagues from provincial, territorial, and federal agencies who have worked to create the large fire database, particularly Kim Logan. We especially thank Brian Stocks and the late Bernie Todd for their leadership in this area. We thank Lynn Gowman, Eric Kasischke, and one anonymous reviewer for comments on the manuscript. The development of the database was partially supported by federal programs including the Climate Change Action Fund, Action Plan 2000, and the Program on Energy Research and Development. The present analysis was partially supported by an Natural Sciences and Engineering Research Council Discovery Grant to B.D.A.

References

Amiro, B.D. 2001. Paired-tower measurements of carbon and energy fluxes following disturbance in the boreal forest. Glob. Change Biol. **7**: 253–268. doi:10.1046/j.1365-2486.2001.00398.x.

Amiro, B.D., Todd, J.B., Wotton, B.M., Logan, K.A., Flannigan, M.D., Stocks, B.J., Mason, J.A., Martell, D.L., and Hirsch, K.G. 2001. Direct carbon emissions from Canadian forest fires, 1959–1999. Can. J. For. Res. **31**: 512–525. doi:10.1139/cjfr-31-3-512.

Amiro, B.D., Logan, K.A., Wotton, B.M., Flannigan, M.D., Todd, J.B., Stocks, B.J., and Martell, D.L. 2004. Fire weather index system components of large fires in the Canadian boreal forest. Int. J. Wildland Fire, **13**: 391–400. doi:10.1071/WF03066.

Andreae, M.O., and Merlet, P. 2001. Emission of trace gases and aerosols from biomass burning. Global Biogeochem. Cycles, **15**: 955–966. doi:10.1029/2000GB001382.

Balshi, M.S., McGuire, A.D., Zhuang, Q., Melillo, J., Kicklighter, D.W., Kasischke, E., Wirth, C., Flannigan, M., Harden, J., Clein, J.S., Burnside, T.J., McAllister, J., Kurz, W.A., Apps, M., and Shvidenko, A. 2007. The role of historical fire disturbance in the carbon dynamics of the pan-boreal region: a process-based analysis. J. Geophys. Res. **112**: G02029 . doi:10.1029/2006JG000380.

Barr, A.G., Griffis, T.J., Black, T.A., Lee, X., Staebler, R.M., Fuentes, J.D., Chen, Z., and Morgenstern, K. 2002. Comparing the carbon budgets of boreal and temperate deciduous forest stands. Can. J. For. Res. **32**: 813–822. doi:10.1139/x01-131.

Begum, B.A., Kim, E., Jeong, C.H., Lee, D.W., and Hopke, P.K. 2005. Evaluation of the potential source contribution function using the 2002 Quebec forest fire episode. Atmos. Environ. **39**: 3719–3724. doi:10.1016/j.atmosenv.2005.03.008.

Bond-Lamberty, B., Peckham, S.D., Ahl, D.E., and Gower, S.T. 2007. Fire as the dominant driver of central Canadian boreal forest carbon balance. Nature (London), **450**: 89–92. doi:10.1038/nature06272. PMID:17972883.

Chen, W.J., Black, T.A., Yang, P.C., Barr, A.G., Neumann, H.H., Nesic, Z., Blanken, P.D., Novak, M.D., Eley, J., Ketler, R.J., and Cuenca, A. 1999. Effects of climatic variability on the annual carbon sequestration by a boreal aspen forest. Glob. Change Biol. **5**: 41–53. doi:10.1046/j.1365-2486.1998.00201.x.

Cofer, W.R., III, Levine, J.S., Winstead, E.L., and Stocks, B.J. 1990. Gaseous emissions from Canadian boreal forest fires. Atmos. Environ. **24A**: 1653–1659.

Cofer, W.R., III, Winstead, E.L., Stocks, B.J., Goldammer, J.G., and Cahoon, D.R. 1998. Crown fire emissions of CO_2, CO, H_2, CH_4, and TNMHC from a dense jack pine boreal forest fire. Geophys. Res. Lett. **25**: 3919–3922. doi:10.1029/1998GL900042.

Conny, J.M., and Slater, J.F. 2002. Black carbon and organic carbon in aerosol particles from crown fires in the Canadian boreal forest. J. Geophys. Res. **107**. doi:10.1029/2001JD001528.

Coursolle, C., Margolis, H.A., Barr, A.G., Black, T.A., Amiro, B.D., McCaughey, J.H., Flanagan, L.B., Lafleur, P.M., Roulet, N.T., Bourque, C.P.A., Arain, M.A., Wofsy, S.C., Dunn, A., Morgenstern, K., Orchansky, A.L., Bernier, P.Y., Chen, J.M., Kidston, J., Saigusa, N., and Hedstrom, N. 2006. Late-summer carbon fluxes from Canadian forests and peatlands along an east-west continental transect. Can. J. For. Res. **36**: 783–800. doi:10.1139/x05-270.

de Groot, W.J., Pritchard, J.M., and Lynham, T.J. 2009. Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. Can. J. For. Res. **39**: 367–382. doi:10.1139/x08-192.

Environment Canada. 2007. Canada's 2005 greenhouse gas inventory: a summary of trends. Available from http://www.ec.gc.ca/pdb/ghg/inventory_report/2005/2005summary_e.cfm [accessed 29 November 2007].

Field, C.B., Lobell, D.B., Peters, H.A., and Chiariello, N.R. 2007. Feedbacks of terrestrial ecosystems to climate change. Annu. Rev. Environ. Resour. **32**: 1–29. doi:10.1146/annurev.energy.32.053006.141119.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., and Stocks, B.J. 2005. Future area burned in Canada. Clim. Change, **72**: 1–16. doi:10.1007/s10584-005-5935-y.

Flannigan, M.D., Stocks, B.J., Turetsky, M.R., and Wotton, B.M. 2008. Impact of climate change on fire activity and fire management in the circumboreal forest. Glob. Change Biol. **14**: 1–12. doi:10.1111/j.1365-2486.2008.01660.x.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian forest fire behavior prediction system. Can. For. Inf. Rep. ST-X-3.

Forster, C., Wandinger, U., Wotawa, G., James, P., Mattis, I., Althausen, D., Simmonds, P., O'Doherty, S., Jennings, S.G., Kleefeld, C., Schneider, J., Trickl, T., Kreipl, S., Jager, H., and Stohl, A. 2001. Transport of boreal forest fire emissions from Canada to Europe. J. Geophys. Res. **106**: 22 887 – 22 906. doi:10.1029/2001JD900115.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and Van Dorland, R. 2007. Changes in atmospheric constituents and in radiative forcing. *In* Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York.

French, N.H.F., Kasischke, E.S., Stocks, B.J., Mudd, J.P., Martell, D.L., and Lee, B.S. 2000. Carbon release from fires in the North American boreal forest. *In* Fire, climate change, and carbon cycling in the boreal forest. *Edited by* E.S. Kasischke and B.J. Stocks. Ecol. Stud. 138. Springer, New York. pp. 377–388.

French, N.H.F., Kasischke, E.S., and Williams, D.G. 2003. Variability in the emission of carbon-based trace gases from wildfire in the Alaskan boreal forest. J. Geophys. Res. **108**. doi:10.1029/2001JD000480. PMID:14686320.

Gillett, N.P., Weaver, A.J., Zwiers, F.W., and Flannigan, M.D. 2004. Detecting the effect of climate change on Canadian forest fires. Geophys. Res. Lett. **31**: L18211. doi:10.1029/2004GL020876.

Goulden, M.L., Winston, G.C., McMillan, A.M.S., Litvak, M.E., Read, E.L., Rocha, A.V., and Elliot, J.R. 2006. An eddy covariance mesonet to measure the effect of forest age on land–atmosphere exchange. Glob. Change Biol. **12**: 2146–2162. doi:10.1111/j.1365-2486.2006.01251.x.

Harden, J.W., Trumbore, S.E., Stocks, B.J., Hirsch, A., Gower, S.T., O'Neill, K.P., and Kasischke, E.S. 2000. The role of fire in the boreal carbon budget. Glob. Change Biol. **6**(Suppl. 1): 174–184. doi:10.1046/j.1365-2486.2000.06019.x.

Hely, C., Bergeron, Y., and Flannigan, M. 2000. Coarse woody debris in the southeastern Canadian boreal forest: composition and load variations in relation to stand replacement. Can. J. For. Res. **30**: 674–687. doi:10.1139/cjfr-30-5-674.

Kajii, Y., Kato, S., Streets, D.G., Tsai, N.Y., Shvidenko, A., Nilsson, S., McCallum, I., Minko, N.P., Abushenko, N., Altyntsev, D., and Khodzer, T.V. 2002. Boreal forest fires in Siberia in 1998: estimation of area burned and emissions of pollutants by advanced very high resolution radiometer satellite data. J. Geophys. Res. **107**. doi:10.1029/2001JD001078.

Kasischke, E.S., and Bruhwiler, L.P. 2003. Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998. J. Geophys. Res. **108**. doi:10.1029/2001JD000461. PMID:14686320.

Kasischke, E.S., and Penner, J.E. 2004. Improving global estimates of atmospheric emissions from biomass burning. J. Geophys. Res. **109**. doi:10.1029/2004JD004972.

Kasischke, E.S., Hyer, E.J., Novelli, P.C., Bruhwiler, L.P., French, N.H.F., Sukhinin, A.I., Hewson, J.H., and Stocks, B.J. 2005. Influences of boreal fire emissions on Northern Hemisphere atmospheric carbon and carbon monoxide. Global Biogeochem. Cycles, **19**: GB1012. doi:10.1029/2004GB002300.

Krawchuk, M.A., Cumming, S.G., and Flannigan, M.D. 2009. Predicted changes in fire weather suggest increases in lightning fire initiation and future area burned in the mixedwood boreal forest. Clim. Change, **92**: 83–97. doi:10.1007/s10584-008-9460-7.

Kurz, W.A., and Apps, M.J. 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecol. Appl. **9**: 526–547. doi:10.1890/1051-0761(1999)009[0526:AYRAOC]2.0.CO;2.

Kurz, W.A., Stinson, G., and Rampley, G. 2007. Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbance? Philos. Trans. R. Soc. B Biol. Sci. **363**: 2261–2269 . doi:10.1098/rstb.2007.2198.

Kurz, W.A., Stinson, G., Rampley, G.J., Dymond, C.C., and Neilson, E.T. 2008. Risk of natural disturbances makes future contribution of Canada's forest to the global carbon cycle highly uncertain. Proc. Natl. Acad. Sci. U.S.A. **105**: 1551–1555. doi:10.1073/pnas.0708133105. PMID:18230736.

Litvak, M., Miller, S., Wofsy, S.C., and Goulden, M. 2003. Effect of stand age on whole ecosystem CO_2 exchange in the Canadian boreal forest. J. Geophys. Res. **108**. doi:10.1029/2001JD000854. PMID:14686320.

Park, R.J., Jacob, D.J., Chin, M., and Martin, R.V. 2003. Sources of carbonaceous aerosols over the United States and implications for natural visibility. J. Geophys. Res. **108**. doi:10.1029/2002JD003190. PMID:14686320.

Podur, J., Martell, D.L., and Knight, K. 2002. Statistical quality control analysis of forest fire activity in Canada. Can. J. For. Res. **32**: 195–205. doi:10.1139/x01-183.

Randerson, J.T., Liu, H., Flanner, M.G., Chambers, S.D., Jun, Y., Hess, P.G., Pfister, G., Mack, M.C., Treseder, K.K., Welp, L.R., Chapin, F.S., Harden, J.W., Goulden, M.L., Lyons, E., Neff, J.C., Schuur, E.A.G., and Zender, C.S. 2006. The impact of boreal forest fire on climate warming. Science (Washington, D.C.), **314**: 1130–1132. doi:10.1126/science.1132075. PMID: 17110574.

Rinsland, C.P., Dufour, G., Boone, C.D., Bernath, P.F., Chiou, L., Coheur, P.-F.T.S., and Clerbaux, C. 2007. Satellite boreal measurements over Alaska and Canada during June–July 2004: simultaneous measurements of upper tropospheric CO, C_2H_6, HCN, CH_3Cl, CH_4, C_2H_2, CH_3OH, HCOOH, OCS, and SF_6 mixing ratios. Global Biogeochem. Cycles, **21**: . doi:10.1029/2006GB002795.

SAS Institute Inc. 2000. SAS OnlineDoc®, Version 8. SAS Institute Inc., Cary, N.C.

Soja, A.J., Cofer, W.R., Shugart, H.H., Sukhinin, A.I., Stackhouse, P.W., McRae, D.J., and Conard, S.G. 2004. Estimating fire emissions and disparities in boreal Siberia (1998–2002). J. Geophys. Res. **109**. doi:10.1029/2004JD004570.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. 2007. Cambridge University Press, Cambridge, UK, and New York.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., and Skinner, W.R. 2002. Large forest fires in Canada, 1959–1997. J. Geophys. Res. **108**. doi:10.1029/2001JD000484.

Turetsky, M., and Wieder, R.K. 2001. A direct approach to quantifying organic matter lost as a result of peatland wildfire. Can. J. For. Res. **31**: 363–366. doi:10.1139/cjfr-31-2-363.

Turetsky, M.R., Wieder, R.K., and Vitt, D.H. 2002. Boreal peatland C fluxes under varying permafrost regimes. Soil Biol. Biochem. **34**: 907–912. doi:10.1016/S0038-0717(02)00022-6.

Turetsky, M.R., Amiro, B.D., Bosch, E., and Bhatti, J.S. 2004. Historical burn area in western Canadian peatlands and its relationship to fire weather indices. Global Biogeochem. Cycles, **18**: GB4014. doi:10.1029/2004GB002222.

Turetsky, M.R., Harden, J.W., Friedl, H.R., Flannigan, M., Payne, N., Crock, J., and Radke, L. 2006. Wildfires threaten mercury stocks in northern soils. Geophys. Res. Lett. **33**: . doi:10.1029/2005GL025595.

Turquety, S., Logan, J.A., Jacob, D.J., Hudman, R.C., Leung, F.Y., Heald, C.L., Yantosca, R.M., Wu, S., Emmons, L.K., Edwards, D.P., and Sachse, G.W. 2007. Inventory of boreal fire emissions for North America in 2004: importance of peat burning and pyroconvective injection. J. Geophys. Res. **112**. doi:10.1029/2006JD007281.

Van Wagner, C.E. 1987. Development and structure of the Canadian forest fire weather index system. Can. For. Serv. For. Tech. Rep. 35.

Wang, C., Bond-Lamberty, B., and Gower, S.T. 2003. Carbon distribution of a well- and poorly-drained black spruce fire chronosequence. Glob. Change Biol. **9**: 1066–1079. doi:10.1046/j.1365-2486.2003.00645.x.

Wiedinmyer, C., Quayle, B., Geron, C., Belote, A., McKenzie, D., Zhang, X., O'Neill, S., and Wynne, K.K. 2006. Estimating emissions from fires in North America for air quality modelling. Atmos. Environ. **40**: 3419–3432. doi:10.1016/j.atmosenv.2006.02.010.

Wotawa, G., and Trainer, M. 2000. The influence of Canadian forest fires on pollutant concentrations in the United States. Science (Washington, D.C.), **288**: 324–328. doi:10.1126/science.288.5464.324. PMID:10764643.

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