Fire behaviour and ecological insights to inform refined carbon emissions estimates for Canadian wildfires

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Note: what is target format and home for this? Is it too niche to be anything other than a info report, or something in *Carbon Balance and Management*?

Introduction

- general introduction on forest carbon accounting in Canada (1 paragraph)
- then talk about how fire in many years is the largest disturbance by area, and that current estimates broadly assume full severity when mapped by NBAC. But, we know that <100% of burned area is high severity from Ellen's work and others.
- to support recent advances in operational burn severity mapping for Canada, the CBM DMs also need to be upgraded.
- In this document, we outline the evidence-based fire DMs proposed.
- From a blend of aggregated field data linked to remotely sensed severity, as well as insights from fire physics and experimental fires.
- Key knowledge gaps are also highlighted, with interim solutions presented until further quantification can be done in field studies (could be wildfire, experimental fires, or prescribed fires).

Methods

Combustion gas emission ratios

Certain variables, like the fractionation of CO2:CH4:CO, are constant throughout ecozones, but vary by flaming vs smouldering. They are defined in a global variables table:

FlamingCO2	FlamingCH4	FlamingCO	SmoulderingCO2	SmoulderingCH4	SmoulderingCO
0.89	0.004	0.07	0.79	0.013	0.16

where CO2 is responsible for 89% of emissions in the flaming phase, but only 79% of emissions in the smouldering phase, with a doubling of CO emissions and tripling of CH4 emissions. With a Global Warming Potential of CO equal to 1.9 and CH4 of 25, the Global Warming Potential per unit of biomass consumption in the smouldering phase is 1.26 times higher in global warming potential compared to flaming, not including differential aerosol production and injection heights, however. Note that these proposed emissions factors for flaming vs smouldering are aligned with those currently used in Canada's operational wildfire smoke air quality model, FireWork (Chen et al. 2019). With flaming and smouldering each contributing roughly equally to wildfire emissions, these distinct flaming and smouldering emissions rates correspond well with aircraft smoke chemistry observations by (Simpson et al. 2011) and (Hayden et al. 2022) and are themselves very similar to prior emissions factors used in CBM. Note that as current described, the sum of CO2, CH4, and CO emissions from wildfires only represent approximately 95% of the fire carbon mass emitted to the atmosphere, with 0.5-2.0% of biomass emitted as particulate matter (e.g. PM2.5, but also PM1 and PM10 classes of particulates at 1 and 10 um diameters, respectively), and an additional 5% (Hayden et al. 2022) to as little as 1% (Simon et al. 2010) composed of non-methane organic gases that have a large range in global warming potentials as compared to CH4.

Canopy mortality from plot and remotely sensed data

Ellen to insert methods here

Duff Consumption

While consumption of fine fuels in the litter layer of the forest floor is nearly complete for any given fire intensity, consumption of deeper organic soil horizons (F+H layers in upland forests and upper peat layers in wetlands) is more drought dependent. In this scheme, we utilize the Forest Floor Fuel Consumption (FFFC) model of (Groot, Pritchard, and Lynham 2009), modified to only account for fuel horizons below the litter layer:

$$FFFC = 0.016872DC^{0.71}(FFFL - LL)^{0.671} - LL$$

where DC is the Fire Weather Index Drought Code and FFFL is the Forest Floor Fuel Load (with ecozone averages given in (Letang and Groot 2012) or site-level data). LL is the Litter Load, and is typically on the order of 0.2 kg/m2 for most boreal forest upland and peatland sites ((Thompson et al. 2017)). This distinction is necessary due to the flaming phase consumption of the litter layer as opposed to the smouldering phase consumption of deeper horizons. While ultimately this scheme can be used on individual fires with estimated or measured fuel loading and specific Drought Code values, here we use ecozone-averaged fuel loads and decadal composites of Drought Code to provide representative values. Specifically, a median Drought Code of detected fire hotspots in Canada from 2003-2021 using the same data as the Canadian CFEEPS-FireWork wildfire air quality model of (Chen et al. 2019) is presented below, along with proportional consumption values of the forest floor by ecozone:

Ecozone	Median.DC.of.burning	Median.Forest.Floor.Load.kg.m2	Forest.Floor.consump.kg.m2	Forest.Floor.consump.frac
AM	270	1.45	0.9	0.62
TP	369	14.75	6.57	0.45
TSW	297	1.45	0.98	0.68
BSW	239	8.55	3.23	0.38
BP	242	9.55	3.53	0.37
P	242	9.55	3.53	0.37
TC	254	8.06	3.24	0.4
BC	250	8.06	3.2	0.4
PM	268	14.95	5.24	0.35
MC	452	5.75	3.94	0.68
HP	204	7.65	2.63	0.34
TSE	98	1.45	0.31	0.21
BSE	123	10.65	2.26	0.21

Key calculations in fire C emissions

Go over 4-5 key equations: CFB From mortality, etc. Spell out the equations.

Constructing fire disturbance matrices

First, a generic template for a fire DM is loaded, that can represent any ecozone. It comes in two parts: (1) a list of variables, some biophysical and not relating to fire severity (such as the portion of live branchwood that falls into the smaller size fraction); or (2) severity-specific variables (such as Crown Fraction Burn) for a severity class. The template is loaded, and replicated across the list of ecozones (or any spatial unit) desired. Other processes, such as the analysis of field data, can then be used to fill in ecozone-specific variables in severity classes.

An example of the variable definition template is as follows:

A plain language name for each variable is provided right in the data, as well.

A second template defines each flux in a Disturbance Matrix, with Source and Sink defined as precise character variables, and a plain language summary ("Process Synonym") included

Ecozone	Pool	Plain.Language.Name	Variable.Name	Value	SeverityClass	InterimValue
AM	Other	Portion of bark pool consumed in fire	Bark.Comb.Frac	0.01	Low	TRUE
TP	Other	Portion of bark pool consumed in fire	Bark.Comb.Frac	0.01	Low	TRUE
TSW	Other	Portion of bark pool consumed in fire	Bark.Comb.Frac	0.01	Low	TRUE
BSW	Other	Portion of bark pool consumed in fire	Bark.Comb.Frac	0.01	Low	TRUE
BP	Other	Portion of bark pool consumed in fire	Bark.Comb.Frac	0.01	Low	TRUE
P	Other	Portion of bark pool consumed in fire	Bark.Comb.Frac	0.01	Low	TRUE

to tie this flux back to language used in the fire science literature. Pseudocode and notes are included in each flux, which is repeated for each fire severity class and ecozone. There are 3900 total fluxes, though many do not have sufficient information to describe differences between ecozones. Many of these are computed automatically, tying back into variables such as Crown Fraction Burned.

Ecozone	FluxID	Source	Sink	ProcessSynonym	Pseudocode	Notes	SeverityClass	Value	InterimValue
AM	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers	1-mortality rate	Ellen provides	Low	0.8	TRUE
TP	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers	1-mortality rate	Ellen provides	Low	0.8	TRUE
TSW	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers	1-mortality rate	Ellen provides	Low	0.8	TRUE
BSW	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers	1-mortality rate	Ellen provides	Low	0.8	TRUE
BP	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers	1-mortality rate	Ellen provides	Low	0.8	TRUE
P	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers	1-mortality rate	Ellen provides	Low	0.8	TRUE

With both generic ecozone variables as well as severity-specific variables defined and the pseudocode for each flux included, actual DM values are computed as references to tables, subset by ecozone and severity class:

```
# SourceSink$Value[SourceSink$Ecozone == ecozone &
# SourceSink$FluxID == 1 & SourceSink$SeverityClass ==
# 'Low'] <- 1 - (VarDefs$Value[VarDefs$Variable.Name ==
# 'SW.CFB' & VarDefs$Ecozone == ecozone &
# VarDefs$SeverityClass == 'Low'])
```

Note that rather than defining softwood crown fraction burned as a variable called "SW.CFB.Boreal.Plains" for each ecozone, there is a row in the VarDefs table that represents SW.CFB in each ecozone and for each severity class, thus avoiding the creation of large lists of manually entered variable names and values in the R environment. Instead, these values can be programmatically entered via external analysis of plot data (not covered here).

And make a checksum table to ensure all the major pools sum of up 1:

```
[1] "Softwood Merchantable"
[1] 1
[1] "Softwood Foliage"
[1] 0.964
[1] "Softwood Other"
[1] 1
[1] "Softwood Submerchantable"
```

```
[1] 1
[1] "Softwood Coarse Roots"
[1] 1
[1] "Softwood Fine Roots"
[1] 1
[1] "Aboveground Very Fast DOM"
[1] 0.964
[1] "Aboveground Fast DOM"
[1] 0.969845
[1] "Medium DOM"
[1] 0.963
[1] "Aboveground Slow DOM"
[1] 0.98631
[1] "Softwood Stem Snag"
[1] 0.973
[1] "Softwood Branch Snag"
[1] 0.973
[1] "Hardwood Merchantable"
[1] 1
[1] "Hardwood Foliage"
[1] 0.964
[1] "Hardwood Other"
[1] 1
[1] "Hardwood Submerchantable"
[1] 1
[1] "Hardwood Coarse Roots"
[1] 1
[1] "Hardwood Fine Roots"
[1] 1
[1] "Hardwood Stem Snag"
[1] 0.973
[1] "Hardwood Branch Snag"
[1] 0.973
```

In a final step, a classical tabular DM is show, with row and column names precisely matching those in the Sink and Source columns in the SourceSink table:

Table 1: Example moderate severity DM in Boreal Plains

	Softwood Merchantable	Softwood Stem Snag	Softwood Foliage	Above Ground Very Fast soil C	CO2	CH4	CO
Softwood Merchantable	0.5	0.5					
Softwood Stem Snag		0.0			0.445	0.002	0.035
Softwood Foliage			0	0.45	0.445	0.002	0.035
Above Ground Very Fast soil C							
CO2							
CH4							
CO							

Results

Compare high severity-only C estimates from prior DMs to those with mixed severity.

Discussion

Comparison to prior wildfire emissions estimates (assumption of 100% CFB or else based on FWI+spread day alone).

Conclusions

Data availability

FAIR principle statement

References

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