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

Relevant biomass pools of CBM

Short section explaining the pool definitions most relevant to fire.

Logical structure

To simpllify the process of the creation of the DMs as a distillation of the complexities of fire severity and combustion patterns, the following logical axioms are proposed and maintained throughout:

1. DMs should be in terms of mortality, not survival
2. Crown Fraction Burned (CFB) is a mass-based estimate of the portion of foliage consumed in flaming, and is inclusive of merchantable and submerchantable trees, both broadleaf and needleleaf
3. Snags are inclusive of both those killed by prior fire as well as those killed by all other causes
4. In submerchantable trees, mortality = CFB
5. In submerchantable trees, mortality is <= 1
6. In merchantable stands, CFB < mortality
7. Survival = 1 - mortality
8. CFB < survival
9. The girdled fraction of trees = mortality - CFB
10. Survival <= 1 and also >= 0

Of these, Crown Fraction Burned (CFB) is both highly critical and a concept used primarily in fire behaviour science but not carbon accounting nor fire ecology. CFB was introduced in the 1992 Fire Behaviour Prediction System documentation, and provides a simple continuous 0-100 variable for only the consumption of foliage (inclusive of both conifer and broadleaf), as opposed to ordinal and less precise systems like Crown Fire Severity Index that allows the user to specify moreso which pools of canopy biomass are consumed, but not the degree to which a given pool is consumed.

Canopy mortality from plot and remotely sensed data

Ellen to insert methods here

… the resulting field-based estimates of crown mortality by ecozone are as follows:

The other key ecozone and severity-dependent variable provided by field data is the area-wise fraction of completely unburned forest floor, which varies widely by severity class:

Table 1: Softwood fractional mortality by ecozone, as dervied from median values from field studies

Ecozone	Low	Mod	High
AM	0.28	0.34	0.95
BC	0.24	0.65	0.98
BP	0.45	0.81	1.00
BSE	0.45	0.81	1.00
BSW	0.45	0.81	1.00
HP	0.45	0.81	1.00
MC	0.28	0.74	0.98
MP	0.28	0.34	0.95
P	0.45	0.81	1.00
PM	0.13	0.38	0.97
TC	0.24	0.65	0.98
TP	0.45	0.81	1.00
TSE	0.10	0.81	1.00
TSW	0.10	0.81	1.00

Table 2: Unburned litter area by ecozone and severity class. The majority of the data comes from studies in the Boreal Plains and Boreal Shield West, and so values are extrapolated from those two well-observed ecozones to all others.

Ecozone	Low	Mod	High
AM	0.14	0.06	0.02
BC	0.14	0.06	0.02
BP	0.14	0.06	0.02
BSE	0.20	0.08	0.05
BSW	0.20	0.08	0.05
HP	0.20	0.08	0.05
MC	0.14	0.06	0.02
MP	0.14	0.06	0.02
P	0.14	0.06	0.02
PM	0.14	0.06	0.02
TC	0.14	0.06	0.02
TP	0.14	0.16	0.03
TSE	0.20	0.08	0.05
TSW	0.20	0.08	0.05

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:

Table 3: Fire Weather, fuel loading, and duff consumption values per ecozone

Ecozone	Median.DC.of.burning	Median.Duff.Load.kg.m2	Duff.consump.kg.m2	Duff.consump.frac
AM	270	10.65	4.14	0.4
TP	369	14.75	6.57	0.45
TSW	297	1.45	0.98	0.82
BSW	239	8.55	3.23	0.39
BP	242	9.55	3.53	0.38
P	242	9.55	3.53	0.38
TC	254	8.06	3.24	0.41
BC	250	8.06	3.2	0.41
PM	268	14.95	5.24	0.36
MC	452	5.75	3.94	0.72
HP	204	7.65	2.63	0.36
TSE	98	1.45	0.31	0.26
BSE	123	10.65	2.26	0.22

Key calculations in fire C emissions

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

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:

Table 4: Emissions ratios in flaming and smouldering phase, updated to reflect values used in Canada's operational wildfire smoke emissions model, CFFEPS-Firework

FlamingCO2	FlamingCH4	FlamingCO	SmoulderingCO2	SmoulderingCH4	SmoulderingCO
0.9	0.01	0.09	0.9	0.01	0.09

where CO2 is responsible for 90% of emissions in the flaming phase, but only 90% 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 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.

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

Table 5: Example of stored fire disturbance matrix precursor variable information

Ecozone	Pool	Plain.Language.Name	Variable.Name	Value	SeverityClass	InterimValue	Notes
AM	Branch	Softwood small branch fraction of total branchwood	SW.SmBranch.frac.of.tot.BW	0.5	NA	TRUE	
AM	Branch	Hardwood small branch fraction of total branchwood	HW.SmBranch.frac.of.tot.BW	0.5	NA	TRUE	
AM	Other	Softwood branchwood as portion of total "other" pool	SW.BW.frac.of.other	0.4	NA	TRUE	
AM	Other	Hardwood branchwood as portion of total "other" pool	HW.BW.frac.of.other	0.4	NA	TRUE	
AM	Other	Hardwood Bark as portion of "other" pool	HW.bark.frac.of.other	0.1	NA	TRUE	
AM	Other	Softwood Bark as portion of "other" pool	SW.bark.frac.of.other	0.1	NA	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.

Table 6: Sample of disturbance matrix data file

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.

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).

A classic checksum table to ensure all the major pools sum of up 1 is presented below (Boreal Plains, high severity), but keep in mind that the sum of combusted pools is longer precisely 1.0 since particulate matter and non-methane hydrocarbons are accounted as leaving the biomass pool but have no corresponding atmospheric pool at the moment:

```
[1] "Softwood Merchantable"
[1] 1
[1] "Softwood Foliage"
[1] 1
[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] 1
[1] "Aboveground Fast DOM"
[1] 1
[1] "Medium DOM"
[1] 1
[1] "Aboveground Slow DOM"
[1] 1
[1] "Softwood Stem Snag"
[1] 1
[1] "Softwood Branch Snag"
[1] 1
[1] "Hardwood Merchantable"
[1] 1
[1] "Hardwood Foliage"
[1] 1
[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] 1
[1] "Hardwood Branch Snag"
[1] 1
```

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 7: Low severity Disturbance Matrix in BP

	Softwood Merchantable	Softwood Stem Snag	Medium DOM	Softwood Foliage	Above Ground Very Fast DOM	CO2	CH4	CO
Softwood Merchantable	1	0.00						
Softwood Stem Snag		0.45	0.4500			0.09000	0.001000	0.009000
Medium DOM			0.0868			0.82188	0.009132	0.082188
Softwood Foliage				0.55		0.00000	0.000000	0.000000
Above Ground Very Fast DOM								
CO2								
CH4								
CO								

Table 8: Mod severity Disturbance Matrix in BP

	Softwood Merchantable	Softwood Stem Snag	Medium DOM	Softwood Foliage	Above Ground Very Fast DOM	CO2	CH4	CO
Softwood Merchantable	0.19	0.81						
Softwood Stem Snag		0.00	0.9000			0.09000	0.001000	0.009000
Medium DOM			0.0372			0.86652	0.009628	0.086652
Softwood Foliage				0.19		0.72900	0.008100	0.072900
Above Ground Very Fast DOM								
CO2								
CH4								
CO								

Table 9: High severity Disturbance Matrix in BP

	Softwood Merchantable	Softwood Stem Snag	Medium DOM	Softwood Foliage	Above Ground Very Fast DOM	CO2	CH4	CO
Softwood Merchantable	0	1						
Softwood Stem Snag		0	0.9000			0.09000	0.001000	0.009000
Medium DOM			0.0124			0.88884	0.009876	0.088884
Softwood Foliage				0		0.90000	0.010000	0.090000
Above Ground Very Fast DOM								
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).

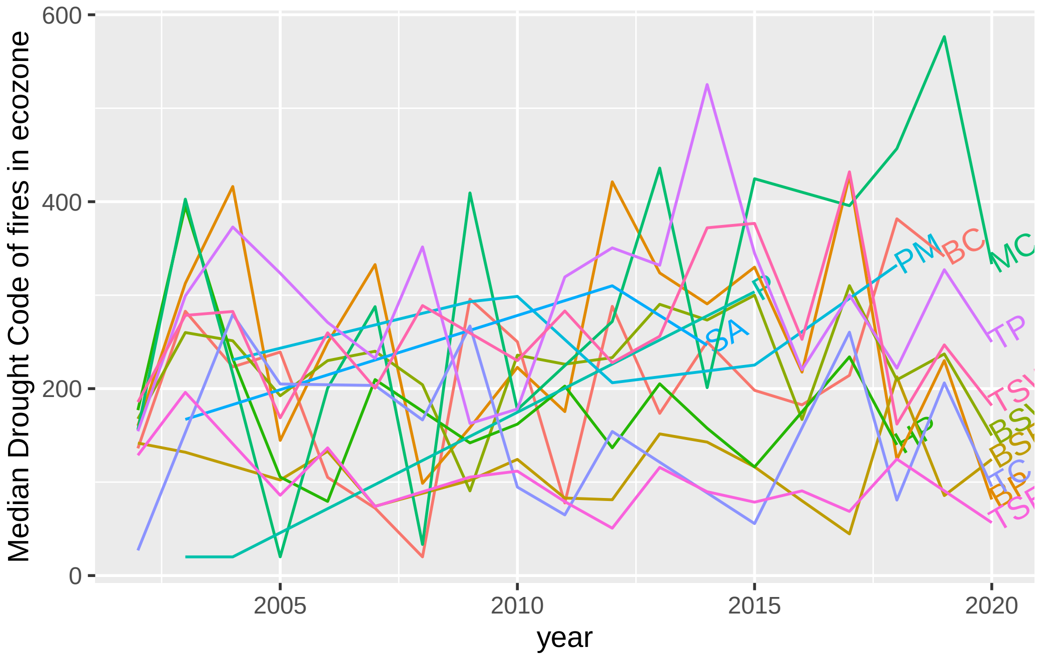
Conclusions

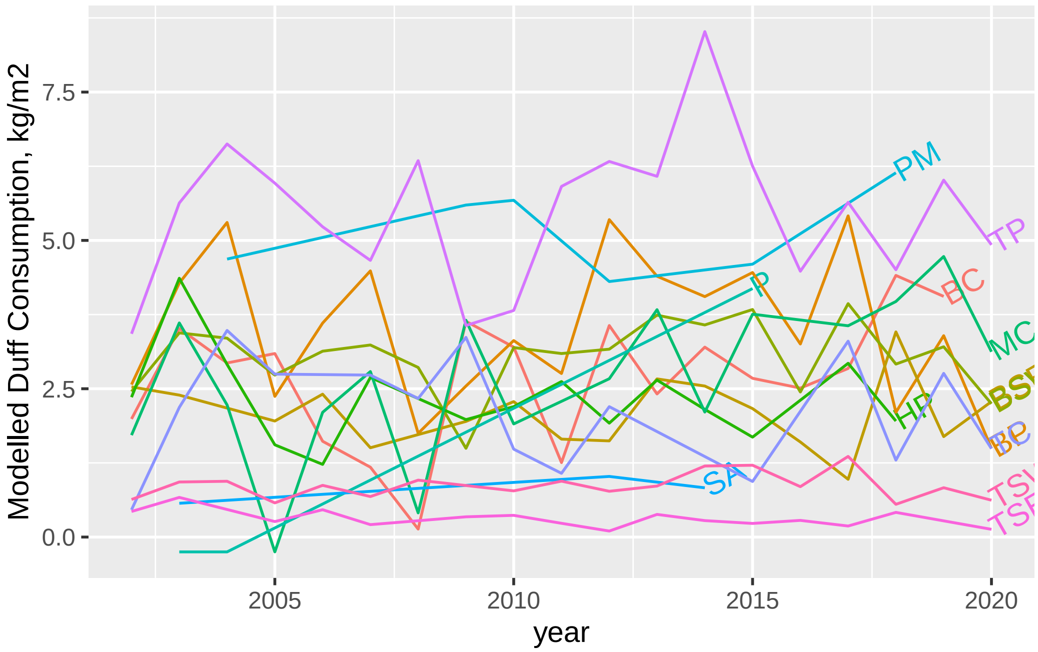
Data availability

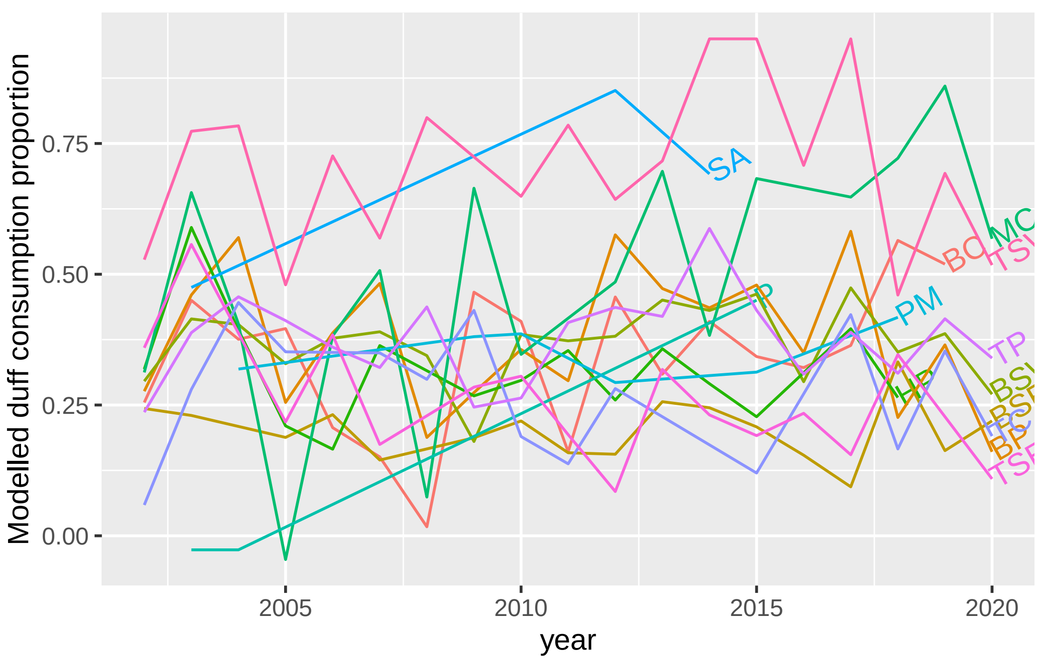
FAIR principle statement

Appendix A: list of fluxes and corresponding fire-related plain-language summary.

Appendix B: annual variability in observed Drought Code during wildfire spread, and impact on ecozone-level DM calculations




Modelled Duff Consumption, kg/m2
7.5
5.0
2.5
0.0
2005
2010
2015
2020
year
PM
TP
BC
MC
HP
SA
P


Modelled duff consumption proportion
0.75
0.50
0.25
0.00
2005
2010
2015
2020
year
SA
MC
BC
PM
TP
HP
P

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Source	Sink	ProcessSynonym
Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers
Softwood Merchantable	Softwood Stem Snag	Mortality rate of large conifers
Softwood Merchantable	Black Carbon	Live conifer to BC rate
Softwood Foliage	Softwood Foliage	Green fraction of canopy remaining intact after fire
Softwood Foliage	Aboveground Very Fast DOM	Post-fire litterfall (heat-killed but not burned)
Softwood Foliage	CO_2	Crown Fraction Burned
Softwood Foliage	CH_4	Crown Fraction Burned
Softwood Foliage	CO	Crown Fraction Burned
Softwood Other	Softwood Other	unconsumed Live branches, stumps and small trees including bark
Softwood Other	Softwood Branch Snag	Portion of ”other” pool as killed by fire but unconsumed branches
Softwood Other	CO_2	Proportional Combustion sum of branches, stumps, small trees and bark
Softwood Other	CH_4	Proportional Combustion sum of branches, stumps, small trees and bark
Softwood Other	CO	Proportional Combustion sum of branches, stumps, small trees and bark
Softwood Submerchantable	Softwood Submerchantable	Understory conifer survival rate
Softwood Submerchantable	Softwood Branch Snag	Understory conifer branches killed but not consumed
Softwood Submerchantable	CO_2	Understory Conifer consumption rate
Softwood Submerchantable	CH_4	Understory Conifer consumption rate
Softwood Submerchantable	CO	Understory Conifer consumption rate
Softwood Coarse Roots	Softwood Coarse Roots	Surviving coarse roots in conifers
Softwood Coarse Roots	Aboveground Fast DOM	Coarse Roots killed in fire but not combusted in organic soil
Softwood Coarse Roots	Belowground Fast DOM	Coarse Roots killed in fire but not combusted in mineral soil
Softwood Fine Roots	Softwood Fine Roots	Surviving fine roots
Softwood Fine Roots	Aboveground Very Fast DOM	Fine roots killed but not burned in organic soil
Softwood Fine Roots	Belowground Very Fast DOM	Fine roots killed but not burned in mineral soil
Softwood Fine Roots	CO_2	Fine roots combusted alongside duff
Softwood Fine Roots	CH_4	Fine roots combusted alongside duff
Softwood Fine Roots	CO	Fine roots combusted alongside duff
Hardwood Merchantable	Hardwood Merchantable	Survival rate of broadleaf trees
Hardwood Merchantable	Hardwood Stem Snag	Mortality rate of broadleaves
Hardwood Merchantable	Black Carbon	Live broadleaf stemwood to black carbon (incomplete combustion) rate
Hardwood Foliage	Hardwood Foliage	Green fraction of canopy
Hardwood Foliage	Aboveground Very Fast DOM	Post-fire litterfall
Hardwood Foliage	CO_2	Crown Fraction Burned
Hardwood Foliage	CH_4	Crown Fraction Burned
Hardwood Foliage	CO	Crown Fraction Burned
Hardwood Other	Hardwood Other	Surviving Live branches, stumps and small trees including bark
Hardwood Other	Hardwood Branch Snag	Portion of ”other” pool as dead but unburned large branches
Hardwood Other	CO_2	Proportional Combustion sum of branches, stumps, small trees and bark
Hardwood Other	CH_4	Proportional Combustion sum of branches, stumps, small trees and bark
Hardwood Other	CO	Proportional Combustion sum of branches, stumps, small trees and bark
Hardwood Submerchantable	Hardwood Submerchantable	Understory broadleaf survival rate
Hardwood Submerchantable	Hardwood Branch Snag	Understory broadleaf mortality rate
Hardwood Submerchantable	CO_2	Understory Broadleaf consumption rate
Hardwood Submerchantable	CH_4	Understory Broadleaf consumption rate
Hardwood Submerchantable	CO	Understory Broadleaf consumption rate
Hardwood Coarse roots	Hardwood Coarse roots	Surviving deciduous coarse roots
Hardwood Coarse roots	Aboveground Fast DOM	Deciduous coarse roots in the duff that are killed but unconsumed
Hardwood Coarse roots	Belowground Fast DOM	Deciduous coarse roots in the mineral soil that are killed but unconsumed
Hardwood Fine Roots	Hardwood Fine Roots	Surviving fine roots
Hardwood Fine Roots	Aboveground Very Fast DOM	Fine roots killed but not burned in organic soil
Hardwood Fine Roots	Belowground Very Fast DOM	Fine roots killed but not burned in mineral soil
Hardwood Fine Roots	CO_2	Fine roots combusted alongside duff
Hardwood Fine Roots	CH_4	Fine roots combusted alongside duff
Hardwood Fine Roots	CO	Fine roots combusted alongside duff
Aboveground Very Fast DOM	Aboveground Very Fast DOM	Unburned fraction of The L horizonb comprised of foliar litter plus dead fine roots, approximately <5 mm diameter
Aboveground Very Fast DOM	CO_2	Combusted fraction of litter layer
Aboveground Very Fast DOM	CH_4	Combusted fraction of litter layer
Aboveground Very Fast DOM	CO	Combusted fraction of litter layer
Belowground Very Fast DOM	Belowground Very Fast DOM	Uncombusted Fraction of Dead fine roots in the mineral soil, approximately <5 mm diameter
Aboveground Fast DOM	Aboveground Fast DOM	Uncombusted Fine and small woody debris plus dead coarse roots in the forest floor, approximately <75 mm diameter
Aboveground Fast DOM	CO_2	Combusted FWD+MWD fraction (dead course roots accounted for in AG Slow DOM)
Aboveground Fast DOM	CH_4	Combusted FWD+MWD fraction (dead course roots accounted for in AG Slow DOM)
Aboveground Fast DOM	CO	Combusted FWD+MWD fraction (dead course roots accounted for in AG Slow DOM)
Belowground Fast DOM	Belowground Fast DOM	Uncombusted fraction of Dead coarse roots in the mineral soil, approximately <f2>5 diameter
Medium DOM	Medium DOM	Uncombusted Coarse woody debris on the ground
Medium DOM	CO_2	Combusted fraction of CWD
Medium DOM	CH_4	Combusted fraction of CWD
Medium DOM	CO	Combusted fraction of CWD
Medium DOM	Black Carbon	Medium DOM converted to Black Carbon
Aboveground Slow DOM	Aboveground Slow DOM	Uncombusted fraction of duff and peat horizons
Aboveground Slow DOM	CO_2	Combusted Fraction of duff and peat horizons
Aboveground Slow DOM	CH_4	Combusted Fraction of duff and peat horizons
Aboveground Slow DOM	CO	Combusted Fraction of duff and peat horizons
Belowground Slow DOM	Belowground Slow DOM	Uncombusted fraction of Humified organic matter in the mineral soil
Softwood Stem Snag	Medium DOM	Fraction of conifer snags that fall to ground but not combusted
Softwood Stem Snag	Softwood Stem Snag	Uncombusted fraction of conifer snags (still upright)
Softwood Stem Snag	CO_2	Combusted fraction of conifer snags
Softwood Stem Snag	CH_4	Combusted fraction of conifer snags
Softwood Stem Snag	CO	Combusted fraction of conifer snags
Softwood Stem Snag	Black Carbon	Portion of conifer snags that are converted to Black Carbon upon burning
Softwood Branch Snag	Aboveground Fast DOM	Portion of conifer snag branches that falls onto the ground?
Softwood Branch Snag	Softwood Branch Snag	Unaltered fraction
Softwood Branch Snag	CO_2	Portion of conifer branch snags that are combusted
Softwood Branch Snag	CH_4	Portion of conifer branch snags that are combusted
Softwood Branch Snag	CO	Portion of conifer branch snags that are combusted
Hardwood Stem Snag	Medium DOM	Portion of deciduous snags that falls onto the ground?
Hardwood Stem Snag	Hardwood Stem Snag	Unaltered stem snag fraction
Hardwood Stem Snag	CO_2	Combusted fraction of deciduous snags
Hardwood Stem Snag	CH_4	Combusted fraction of deciduous snags
Hardwood Stem Snag	CO	Combusted fraction of deciduous snags
Hardwood Stem Snag	Black Carbon	Portion of deciduous snags that are converted to Black Carbon upon burning
Hardwood Branch Snag	Aboveground Fast DOM	Portion of deciduous snag branches that falls onto the ground?
Hardwood Branch Snag	Hardwood Branch Snag	Portion of deciduous snag branches that survive a fire
Hardwood Branch Snag	CO_2	Combusted fraction of deciduous snag branches
Hardwood Branch Snag	CH_4	Combusted fraction of deciduous snag branches
Hardwood Branch Snag	CO	Combusted fraction of deciduous snag branches
Black Carbon	Black Carbon	Unburned black carbon fraction
Black Carbon	CO_2	Black carbon combustion fraction
Black Carbon	CH_4	Black carbon combustion fraction
Black Carbon	CO	Black carbon combustion fraction