Incorporating fire severity for refined data-drive carbon emissions estimates of boreal and temperate forest fires in the Generic Carbon Budget Model (GCBM)

[ ][1], [2], [3], [1], [3], and [3]

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Abstract. Wildfire is the most impactful natural disturbance to Canada's boreal and temperate forest biomes. Current representations of fire impact on forest carbon stocks is limited to a single parameterization of fire severity (i.e. the fraction of biomass consumed) that assumes only high severity fires, despite a large and increasing evidence base of widespread mixed-severity wildfire. In this submodel of the larger Generic Carbon Budget Model for forest carbon accounting, field measurements of biomass consumption as related to satellite-derived burn severity maps are interpretted from a fire physics and ecology perspective to derive algorithms to describe forest carbon fluxes in the immediate aftermath of fires.

1 Introduction

general introduction on forest carbon accounting in Canada (1-2 paragraphs) and the concept of fire severity overall, and how these two relate. Managed vs unmanaged forest natural disturbance accounting in Canada, explain that part.

Wildfire is on par with insects as the largest stand-replacing disturbance process in Canada's forest, impacting ~1-3 Mha of Canada's 355 Mha forested area in a typical year (Hanes et al., 2019). In Canada's reliable 40-year burned area record, six years have exceeded 4 Mha of burned area, largely in continental boreal and dry temperate forests west of the Great Lakes. Of this, managed forest accounts for xxx% of the area burned between 1980 and 2022; publicly-owned forest under long-term licence to private timber companies forms the vast majority of Canada's managed forest (Stinson et al., 2019), allowing for simplified and harmonized forest inventory and carbon modelling across jurisdictions (ref??). Burned area is dominated by a relatively small number of very large fires, with 3% of fires constituting 97% of the burned area (Stocks et al., 2002). Lightning-caused fires account for approximately half of all ignitions and between xxx and xxxx% of burned area, but no distinction is made between human and lightning ignition for carbon accounting purposes. Annual burned area mapping at 30 metre resolution is conducted using a composite of satellite and aerial mapping; the relatively small number of large fires, and their slow vegetation regeneration (White et al., 2017) allows for reliable mapping using multispectral imagery such as Landsat within the year of the fire (Whitman et al., 2018).

In CBM-CFS, spatially referenced stand lists representing large homogenous stands that fall within spatial units (ecozone-provincial intersections) are randomly (??) drawn, even when applying precisely mapped burned areas. In Canada's forests, a combination of disturbance history (), soils, and less frequently topographic variables determine leading tree species; at local scales (1-100 ha), tree species plays a major role in determining ecosystem susceptibility to fire (Bernier et al., 2016) where older, conifer-dominated forests burn at very high rates relative to adjacent deciduous or mixed stands. Even when deciduous and mixed forests do burn, they do so at consistently lower severity compared to all but the most xeric conifer forests (Whitman et al., 2018). Currently, biomass consumption estimates are based on observed fire weather (and modelled using the Canadian Fire Behaviour Prediction Systems) at the time of satellite fire activity detection, but applied only at this spatially-referenced aggregated scale. Thus, important biases in fire activity towards older and moderate to poorly-drained forests are not resolved, and only a regionally-averaged fire severity is applied.

To support recent advances in operational burn severity mapping for Canada (Whitman et al., 2020) alongside multi-decade reliable burned area records that provide certainty on fire start and end dates (Hall et al., 2020) , the CBM DMs also need to be upgraded.

something about dynamic veg models like landis and how they represent fire disturbance -then how most MRV models and quickly how they do fire disturbance -even a bit on the GFED/GFAS world too

that ESSD frames it well, worth reading the intro part in detail) (recent Smyth and Campbell papers too) (other recent Canadian fire-carbon things, Walker - esp is supports consistent patterns in proportional carbon loss)

In this document, we outline the evidence-based fire Disturbance Matrices updated and designed for a spatially-explicit update to the CBM, anchored in a three severity class paradigm. These fire carbon flux models are built 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, such as from further wildfire observations, experimental fires, or prescribed fires.

2 Methods

2.1 Biomass pools of the Generic Carbon Budget Model

Short section explaining the pool definitions most relevant to fire.

2.2 Axioms of forest carbon budget after fire

To simplify 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. Disturbance matrices are to 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.

2.3 Ground plot and remotely sensed fire severity data

!!!Ellen to insert methods here - including the figure of where the samples are from etc.

2.4 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:

where CO_2 is responsible for 86.8% of emissions in the flaming phase, but only 70.3% of emissions in the smouldering phase, with a doubling of CO emissions and tripling of CH_4 emissions. With a Global Warming Potential of CO equal to 1.9 and CH_4 of 25, the Global Warming Potential per unit of biomass consumption in the smouldering phase is 1.18 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

Table 1. Emissions factors in flaming and smouldering phase, expressed as portion of unburned biomass carbon content

Spp	Flaming	Smouldering
CO2	0.868	0.703
CO	0.070	0.161
PM10	0.022	0.048
NMOG	0.016	0.035
PM25	0.019	0.040
CH4	0.005	0.013
BC	0.000	0.000

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 CO_2, CH_4, 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 3% (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 CH_4.

2.5 Litter layer area-wise consumption by severity class

The litter layer forms the first biomass pool in which a spreading fire consumes fuel. In low-severity fires, the litter layer may be consumed little to no underlying duff material consumed, nor any tree mortality (Hessburg et al., 2019). Logically, since litter consumption is required for the ignition of the underlying duff layer, this litter area-wise fractional consumption also informs and constrains duff consumption.

2.6 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 the fire literature in Canada, the soil organic layer is termed Forest Floor Fuel Load (FFFL) and is dominated by the equivalent Belowground Slow pool (BGSlow) in CBM. Typically attention has been paid to the absolute value of Forest Floor Fuel Consumption (FFFC); however in the case of carbon modelling, it is the relative fraction of consumption (FFFC/FFFL) that is of interest. In this scheme, we utilize a composite of wildfire data from (de Groot et al., 2009) alongside the ABoVE duff consumption data , with an alternative modelling approach to compute the relative amount of depth of consumption (scalar from 0 to 1) rather than an absolute value in $\mathrm{kg\,m^{-2}}$ or cm as otherwise done in the literature. A logit transform is used on the scalar data to make it suitable for the fitted non-linear least-squares modelling:

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

$$logit\left(\frac{depthofburn}{prefiredepth}\right) = [3.83(1-e^{(-0.005DC)})] + (-0.718log_e(BGSlow)) \quad (1)$$

where DC is the Fire Weather Index Drought Code, and BGSlow in the CBM (given in Mg C/ha in this equation), and also synonymous with the the Forest Floor Fuel Load (with ecozone averages given in (Letang and de Groot, 2012) or site-level data where observed). The modelling of relative depth of burn had a higher skill than modelling of the relative mass of consumption, given natural variability in soil density with depth.

A conversion factor is then applied to the relative depth of burn data to convert it to a relative mass consumption value. Since organic soil density always increases with depth, this conversion factor from depth to mass is less than one:

$$\left(\frac{massconsumed}{prefiremass}\right) = \left(\frac{depthofburn}{prefiredepth}\right) * CF \quad (2)$$

where the Correction Factor is defined for boreal spruce fuel types as:

$$CF_{spruce} = 1.018(RelativeDepth)^{0}.250 \quad (3)$$

and for all other fuels as

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

Ecozone	Median Drought Code of Burning	Median FFFL kg m-2	FFFC kg m-2	% consumption
BSW	239	8.8	3.7	0.42
TP	369	15	7.01	0.47
TSW	297	1.7	1.33	0.78
BP	242	9.8	3.96	0.4
BC	250	8.31	3.72	0.45
BSE	123	10.9	1.95	0.18
TSE	98	1.7	0.71	0.42
MC	452	6	4.15	0.69
HP	204	7.9	3.02	0.38
TC	254	8.31	3.77	0.45
PM	268	15.2	5.45	0.36
AM	270	10.9	4.62	0.42
P	242	9.8	3.96	0.4

$$CF_{nonspruce} = 0.13(RelativeDepth) + 0.87 \tag{4}$$

with RelativeDepth as a value from 0-1.

While ultimately this scheme can be used on individual fires with estimated or measured fuel loading and specific Drought Code values, for the purposes of this first assessment, an ecozone-averaged fuel load and decadal composites of Drought Code can also be used to provide representative values. Specifically, a median Drought Code of detected fire hotspots in Canada from 2003-2021 (Barber et al.) 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:

Note that the maximum upland Forest Floor Fuel Load is approximately 30 kg m-2 (Letang and de Groot, 2012); higher values are typically seen only in peat ecosystems, where the above Forest Floor Fuel Consumption scheme does not apply. For Canadian peatlands, the CaMP model (Bona et al., 2020) is instead used in CBM. Within CaMP, a separate peatland water model driven by Drought Code determines the thickness of the unsaturated peat layer, and an amount approximating 12% of the thickness of the unsaturated peat is consumed as smouldering consumption. The peat-specific carbon pools and fire Disturbance Matrices are fully described in (Bona et al., 2020); large peatland trees will still utilize the DM scheme described below.

Little data is available on the fraction of woody debris consumption alongside fire severity measurements. Coarse woody debris of overstory stems that makes up 60-80% of woody debris biomass in Canada's boreal and temperate forests (Hanes et al., 2021), with its moisture and consumption patterns largely follows the moisture regime of the Drought Code (McAlpine,

Table 4. Coarse Woody debris consumption rates from pre/post measurements in experimental fires

Ecozone	Low	Mod	High
BSW	0.024	0.163	0.140
TP	0.000	0.218	0.238
TSW	0.000	0.218	0.238
BP	0.359	0.509	0.412
BC	0.024	0.163	0.140
BSE	0.080	0.131	0.182
TSE	0.080	0.131	0.182
MC	0.024	0.163	0.140
HP	0.080	0.131	0.182
TC	0.024	0.163	0.140
PM	0.024	0.163	0.140
AM	0.080	0.131	0.182
MP	0.080	0.131	0.182
P	0.359	0.509	0.412

1995). In this modelling framework, the proportion of coarse (>7.5 cm diameter) and medium (>0.5 cm and <7.5 cm) woody debris consumption is estimated based on detailed measurements of consumption from experimental fires. Coarse Woody Debris is responsible for approximately 50-75% of the total woody debris load in most ecozones, and approximately 60% of the total woody debris consumption. Ecozone-level CWD consumption rates are summarized as:

Note that where historical burn severity data is not available, and instead the fire classification type of surface, intermittent crowning, and active crown fire are used as proxies for low, moderate, and high severity fire, respectively. Fine woody debris <0.5 cm in diameter is consumed at the exact same rate as the litter pool (see section above).

2.7 Drivers of C losses in the tree canopy

2.7.1 Overstory tree mortality and consumption

Numerous process-driven (Michaletz and Johnson, 2006) or empirical (Hood and Lutes, 2017) tree mortality models are present and show significant skill in predicting tree mortality based on fire behaviour (i.e. flame length, rate of spread). Since the driving data in this model is satellite-derived fire severity over the landscape scale, fire behaviour metrics such as flame length or scorching height of bark are not available as a continuous mapped product. Instead, softwood and hardwood overstory mortality is calculated per ecozone as a function of satellite-observed fire severity using aggregated ground plot data:

And since large-diameter, live trees killed by fire do not experience significant live stemwood consumption, the entirety of the live stemwood biomass pool that is killed is transferred to the snag pool. Note that the field data and disturbance modelling

Table 5. Softwood fractional mortality by ecozone, as dervied from median values from field studies

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

undertaken here only accounts for tree mortality within the calender year of the fire, and delayed mortality of over one year has been documented in boreal low and moderate severity fires (Angers et al., 2011)where less than half of total mortality occurs after the year of the fire. Thus, the modelling here does not account for delayed mortality that may extend upwards of 5 years after fire.

Crown Fraction Burned (CFB) speaks to the fraction of the live canopy that is itself consumed in the flaming front. The alternate outcomes being survival of the foliage, or the mortality of the tree without canopy consumption, resulting in the dropping of foliage onto the forest floor. From the axioms stated earlier, the CFB must be lower than or equal to the mortality rate, using field studies that show any partial crown consumption is likely sufficient to result in high rates if not complete mortality (Hood and Lutes, 2017), which is the case in Canada's trees with primarily thin bark. Due to the structure of the CBM, all High Severity fires have their mortality in the merchantable and smaller trees set to exactly 1.0, which is no more than a 5% variance from observed values. From field studies, the following ecozone-specific CFB values are found:

The consumption of live bark biomass is a pool in the model, and consumption rates can be defined by severity class. At the moment, lacking robust field data on bark biomass consumption rates across ecozones and severity classes (which are a small portion of the overall biomass), the bark proportional consumption rate is set to 34% of the overstory mortality rate, based only on a single set well-observed high severity fires in the Taiga Plains by [santín2015].

A major distinction is made between softwood and hardwood trees, where in Canada's boreal forests, a large fraction of hardwood trees (see Appendix E) are able to resprout even when the main stem has been killed by an intense forest fire (Brown

Table 6. Softwood crown fraction burned by ecozone, as dervied from median values from field studies

Ecozone	Low	Mod	High
BSW	0.0	0.81	1.00
TP	0.0	0.81	1.00
TSW	0.1	0.81	1.00
BP	0.0	0.81	1.00
BC	0.0	0.65	0.98
BSE	0.0	0.81	1.00
TSE	0.1	0.81	1.00
MC	0.0	0.74	1.00
HP	0.0	0.81	1.00
TC	0.0	0.65	1.00
PM	0.0	0.38	0.97
AM	0.0	0.34	0.95
MP	0.0	0.34	0.95
P	0.0	0.81	1.00

and DeByle, 1987). Accordingly, the root mortality rates differ greatly between softwoods and hardwoods, with softwood root mortality equal precisely to stem mortality, while in resprouting hardwoods, little root mortality is observed even after intense fire (Pérez-Izquierdo et al., 2019). Though GCBM can resolve a species list down to the pixel level, currently an ecozone-level regional average composition of hardwood species with resprouting traits is used and is shown below:

Concurrently, the fraction of fine roots contained within the combustible forest floor layers can be a close to or exceeding 50% of the fine root biomass (Strong and La Roi, 1985), and burns alongside the organic soils (Benscoter et al., 2011). As a result, the calulation for softwood fine root consumption and mortality are as follows, using Softwood as an example:

$$SWFineRootConsump = SW.Mort \times SW.Prop.Fine.Root.duff \times Duff.Consump.Fract \tag{5}$$

$$SWFineRootMort.AG = SW.Mort \times SW.Prop.Fine.Root.duff \times (1 - Duff.Consump.Fract) \times (1 - ReSproutFactor) SWFine \tag{6}$$

In contrast, the larger diameter of the coarse root biomass pool prevents its consumption during any smouldering of the duff layer, and the mortality rate of coarse roots is simply proportional to that of the stemwood overall.

Table 7. Ecozone-level average fraction of hardwood overstory species that do not suffer extensive belowgroud biomass mortality after fire

Ecozone	Resprout Fraction
BSW	0.75
TP	0.75
TSW	0.94
BP	0.99
BC	0.76
BSE	0.67
TSE	0.78
MC	0.97
HP	0.80
TC	0.27
PM	0.39
AM	0.76
MP	0.32
P	0.99

2.7.2 Understory tree mortality and consumption

Understory (or small diameter overstory) tree mortality is defined seperately in the model, but given the lack of data on diameter classes in the severity data, robust field data on differing mortality rates of smaller diameter trees is not available, and so the understory tree mortality rate is set equal to the overstory rate as defined in the table above. Note that trees with a top height less than 1.4 m are not considered in this pool, and instead are lumped into the “other” pool.

2.7.3 Snag and stump consumption

Compared to live stemwood of the same diameter, the low moisture content of standing dead stemwood (snags) allows for much greater consumption during the passage of an intense flaming front. The snag branch pool experiences almost complete combustion, while the largest biomass pool of the main standing dead stemwood

2.8 Construction fire disturbance matrices

Give total number of global parameters, and parameters per ecozone, and then total parameters, and what % of total parameters we have so far filled with data

3 Results and example applications

Table 8. High severity Disturbance Matrix in BP

	Softwood Merchantable	Softwood Stem Snag	Medium DOM	Softwood Foliage	Aboveground Very Fast DOM	CO2	CH4	CO	PM25
Softwood Merchantable	0	1							
Softwood Stem Snag		0	0.90000			0.0868000	0.0005000	0.0070000	0.0019000
Medium DOM			0.57624			0.2979033	0.0055089	0.0682254	0.0169504
Softwood Foliage				0	0.00	0.8680000	0.0050000	0.0700000	0.0190000
Aboveground Very Fast DOM					0.02	0.8506400	0.0049000	0.0686000	0.0186200
CO2									
CH4									
CO									
PM25									

3.1 Field case studies (for consideration)

```
### table with rows are CBM pools, columns (paird) are obs
### and modelled exp fires

### fires that would work:

### ICFME (SW TP High); Sharpsands 2007 (SW BSE High),
### Lafoe (HW BSE Low), CWS C-7 burns (SW MC Mod), Carrot
### lake (SW MC High)

### variables specifically measured during an experimental
### fire, in the verbiage of the fire DMs:
exp.fire.table.defs <- c("SW.CFB", "HW.CFB", "SW.Mort", "HW.Mort",
    "SW.SubMerch.Mort", "HW.SubMerch.Mort", "SmTree.Mort", "SW.Snag.Comb.Frac",
    "HW.Snag.Comb.Frac", "MedDOM.Comb.Frac", "Duff.consump.frac")

## then, take the list above, and look up the same row but
## the column 'Plain.Language.Name' in FireDMTableDefs.csv:
## exp.fire.table.labels <-

## note that Duff.consump.frac is an ecozone variable, not
## in FireDMTableDefs.csv

## list of all possible CBM pools measured during an
## experimental fire:
exp.fire.pools <- c("Softwood Foliage", "Softwood Other", "Aboveground Very Fast DOM",
    "Aboveground Fast DOM", "Medium DOM", "Aboveground Slow DOM",
    "Softwood Stem Snag", "Hardwood Other", "Hardwood Stem Snag")

### fun idea: ternary plots of live vs combusted vs dead
### for each of these fires, modelled vs observed?
### https://cran.r-project.org/web/packages/Ternary/vignettes/Ternary.html
### with the colour being the fuel type/leading spp and
### size being total emissions?  can we draw lines in
```

```
### between pairs of mod vs obs in that package? TernaryApp
### function in the package should apparently let you draw
### connected points?
```

4 Discussion

-some discussion points (unordered) so far

- given the generic nature of these DMs and their simple relative simplicity, can be added to other frameworks like LANDIS (see Stenzel 2019 as well, they do some of that).
- paragraph on extended impacts like delayed stem mortality, rapid snag fall, and changes (or not) in duff decomposition rates. Not (as of yet) covered in this 1-timestep pulse disturbance described here.

5 Conclusions

The conclusion goes here.

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

7 Appendix B: non-linear least squares modelling of soil organic layer consumption

For national annual estimates of forest organic soil layer consumption during wildfire, implementations that only utilize Canadian experimental fire data from the Fire Behaviour Prediction System will be limited to a maximum consumption value of 5 kg/m2 of total surface fuel (woody debris, litter, and duff) of 5 kg/m2, or 25 Mg C/ha, given the observation dataset and fitted model parameters. For the common C-2 Boreal Spruce fuel type for instance, Surface Fuel Consumption (kg m/2) is modelled as:

$$SFC = 5.0\left(1 - e^{-0.0115BUI}\right)^{1.0} \tag{7}$$

This model form has the distinct advantage of SFC being 0.0 at a BUI of zero. The model parameters vary by fuel type (i.e. deciduous broadleaf fuels are limited to 1.5 kg/m2 of maximum SFC) but are fixed within a fuel type.

More recent observations and modelling from de Groot et al. (2009) extended the FBP data with an additional 128 observations from 7 additional wildfires, and the ABoVE project compiled over 1000 field observations of depth of burn and C stocks before and after wildfire in Canada and Alaska, over 600 of which are in North American Level II ecoregions also occurring in Canada (fix Walker 2020 ORNL DAAC ref in bibtex here). de Groot et al. (2009) provides a concise and informative improvement on the FBP fuel consumption equations, where both a Fire Weather Index System component (in this case, Drought Code) is used similarly to Buildup Index in the FBP, but importantly, the site-level organic soil layer fuel load is also accounted for, which allows for the greater absolute combustion in deeper organic soils that is moderated by the natural logarithm transformation:

$$log_e(FFFC) = -4.252 + 0.710 log_e(DC) + 0.671 log_e(FFFL) \tag{8}$$

where FFFC is Forest Floor Fuel Consumption (SFC minus surface woody debris) in kg m/2 and FFFL is Forest Floor Fuel Load in kg/m2. This model fits well within the dataset and extends the observed maximum FFFC to nearly 10 kg/m2. The ABoVE synthesis of FFFL and FFFC (Walker et al 2020 ORNL) expands upon a slightly smaller dataset used in a modelling summary also by Walker et al (2020 NCC), where structural equation modelling was used to explore drivers of FFFC but no concise and readily reproducible modelling is produced. The results of the SEM from Walker et al (2020 NCC) emphasized a greater role of FFFL over DC, though coarse reanalysis that lacked local fire agency weather stations was used. An analysis of just 2014 fires in the Northwest Territories by (walker2018) showed that while the mean depth of burn across all black spruce stands was 6-10 cm, the driest (xeric) black spruce stands with the smallest FFFL showed upwards of 75% soil organic consumption, while deeper organic soils in subhygric black spruce stands showed less than 25% consumption.

To provide the largest possible dataset for FFFC and FFFL, the ABoVE synthesis was combined with wildfire data from de Groot et al 2009 not otherwise found in the ABoVE synthesis. The ABoVE synthesis sites in the Alaska Boreal Interior ecoregion, which have equivalent Canadian ecozone were excluded, but Alaska Boreal Cordillera sites near the Yukon border were utilized. Experimental fire data from the FBP data was not used, as deeper combustion measurements resulting from hours and days of smouldering combustion captured in wildfire data are not available in experimental fires where extensive smouldering is not measured due to suppression. In order to best represent on-the-ground Fire Weather Index values, the Drought Code and other FWI values from Walker et al 2020 reanalysis were substituted with interpolated weather station (both Environment and Climate Change Canada as well fire agency stations). This data also has the benefit of being properly overwintered for Drought Code (Hanes DC overwinter) and capturing small rain events not captured in reanalysis that meaningfully impact the Duff Moisture Code in particular.

For the purposes of improving national estimates of the fractional soil organic layer loss during wildfire, this framework emphasizes the proportional C stock loss (as with all CBM disturbance matrices) rather than the absolute value of combustion. In contrast to the modelling of absolute combustion value, any analysis of proportions is best conducted as logit- transformed data, where the logit transformation is:

$$logit(p) = log \frac{p}{1-p} \tag{9}$$

which effectively transforms a data of proportions of [0,1] to a Gaussian distribution with a range of approximately -5 to +5 (in this dataset), and a mode approximately at zero. Within the logit-transformed data, exploratory analysis of ecozones as a factor alongside other non-linear splines of FWI values and FFFL was conducted:

##

```
## Family: gaussian
## Link function: identity
##
## Formula:
## prop_sol_combusted_logit ~ s(drought_code, k = 4, bs = "tp") +
##     ecozone + s(BGSlow.Mg.C.ha, k = 4, bs = "tp")
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  0.11939    0.09318   1.281   0.2005
## ecozoneBP   -0.29433    0.15506  -1.898   0.0581 .
## ecozoneBSW  -0.19928    0.15988  -1.246   0.2131
## ecozoneTP   -0.23049    0.11476  -2.008   0.0450 *
## ecozoneTSW  -0.29887    0.12157  -2.458   0.0142 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##                     edf Ref.df       F p-value
## s(drought_code)   1.352  1.618   2.862  0.0631 .
## s(BGSlow.Mg.C.ha) 2.950  2.998 232.720  <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.628   Deviance explained = 63.3%
## -REML = 869.04  Scale est. = 0.81207   n = 651
```

(could also show boxplots?) which shows that the Boreal Cordillera ecozone has a meaningfully higher proportional soil organic layer consumption rate compared to BP, BSW, TP, and TSW, all of which are not significantly different in consumption rates once DC and FFFC (shown as BGSlow.Mg.C.ha) are accounted for. Boreal Cordillera data were set aside for a distinct model.

Similar to de Groot et al. (2009), Drought Code was a better predictor of consumption rates than Buildup Index as used in the FBP. In the logit transformed space, saturation-type non-linear curve using the relevant FWI component was fitted in a non-linear least squares model, but an additive term of the natural-logarithm transformed FFFC (given as BGSlow pool in Mg C/ha) was used as well. In the end, a superior model was found using the proportional depth of burn, rather than the proportional loss of the mass of the soil organic layer. The non-linear least squares model fit was conducted using the Levenberg-Marquardt nonlinear least-squares algorithm found in MINPACK (Elzhov et al 2023) R package, which supported bounded parameter constraints. In the abstract, the model follows the form:

$$logit\left(\frac{depthofburn}{pre-fireorganicdepth}\right) = [3.83 * (1 - e^{(-0.005*DC)})] + (-0.718 * log_e(BGSlow)) \tag{10}$$

In the abstract, the model follows the form:

$$logit\left(\frac{depthofburn}{pre-fireorganicdepth}\right) = [c * (1 - e^{(a*DC)})] + (b * log_e(BGSlow)) \tag{11}$$

Note the “b” coefficient on the parameter associated with the FFFL (BGSlow) of -0.718, which results in larger organic layer fuel loads leading to smaller proportional consumption values, which follows the patterns shown by Walker 2018 for NWT fires of 2014.

The a parameter term that forms the exponent of e alongside Drought Code is related to the DC value at which half of the maximum possible asymptotal consumption value is observed (for a given FFFL value). The NLS fitting was given a minimum value of -0.06 such that half of the asymptotal maximum consumption rate was modelled as occurring at or around a DC value of 300. The other parameters were fit to the best possible value with no constraint.

Importantly, since fire behaviour, emissions modelling, and carbon accounting all operate with the calculation of mass loss and depth of burn, a correction factor was applied that corrects for the trends in bulk density with depth for C-2 fuels as given by de Groot et al. (2009), so that a model of proportional depth of burn is then converted into a proportional mass loss term:

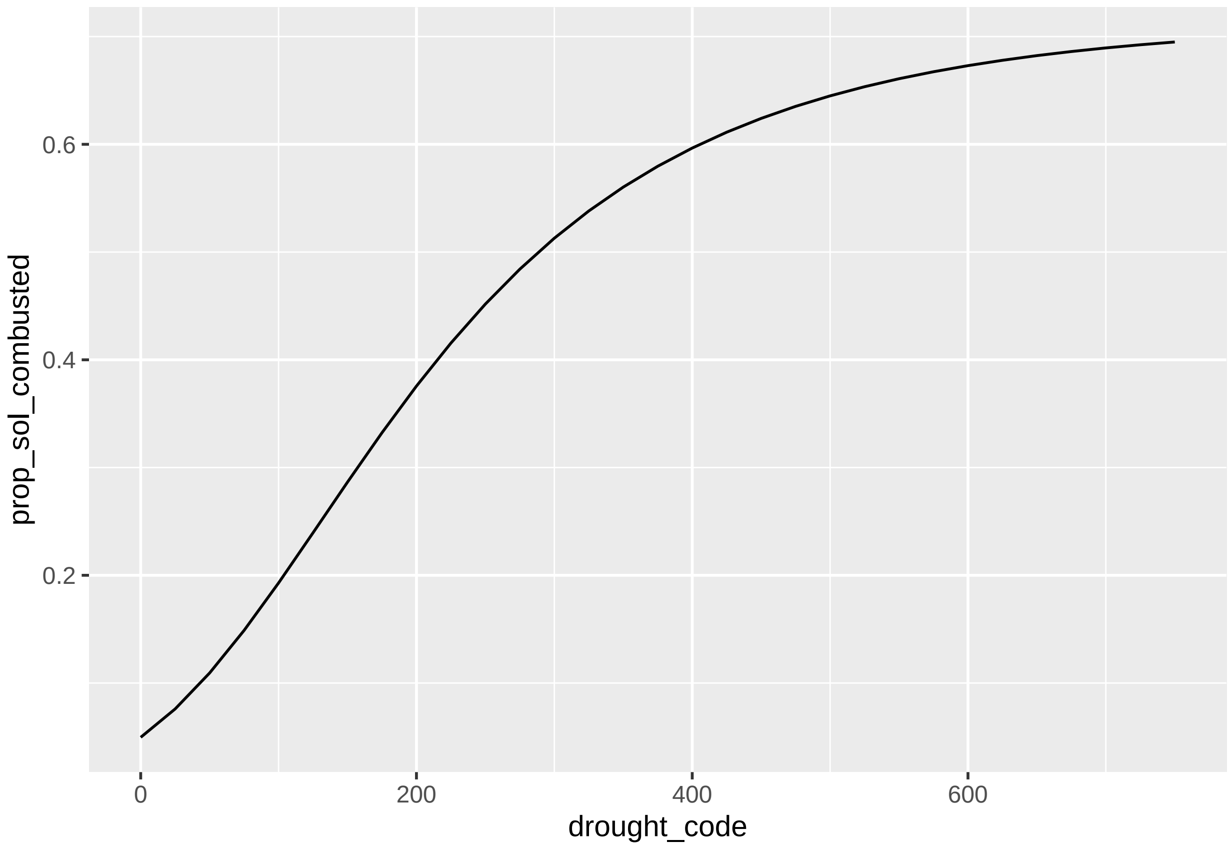
$$\left(\frac{FFFC}{FFFL}\right) = 1.017\left(\frac{depthofburn}{pre-fireorganicdepth}\right)^{0.250} \tag{12}$$

which for example means that the median proportional depth of burn in the AboVE/de Groot training data of 0.40 corresponds to 0.32 of the proportional mass loss (since shallow organic soil is less dense), or a correction factor of 0.80. For non-spruce-dominated fuels, this correction is much smaller but still meaningful:

$$\left(\frac{FFFC}{FFFL}\right) = 0.13\left(\frac{depthofburn}{pre-fireorganicdepth}\right) + 0.87 \tag{13}$$

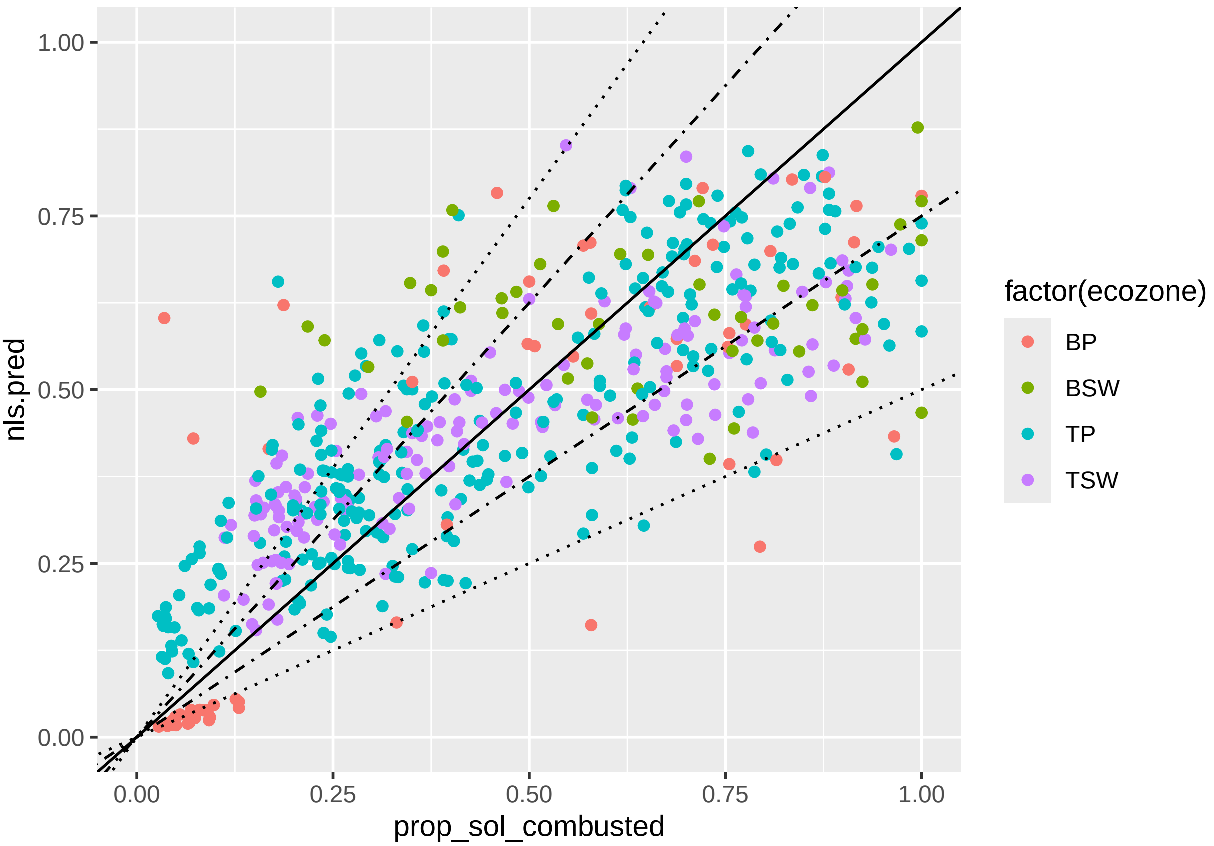
(show perhaps what a few different a values look like?) (also compute the DC value of about half the maximum FBP SFC values too, just for kicks)

For example, using a moderately thick ~12 cm thick organic soil layer, the proportion of consumption as a function of Drought Code using the model above

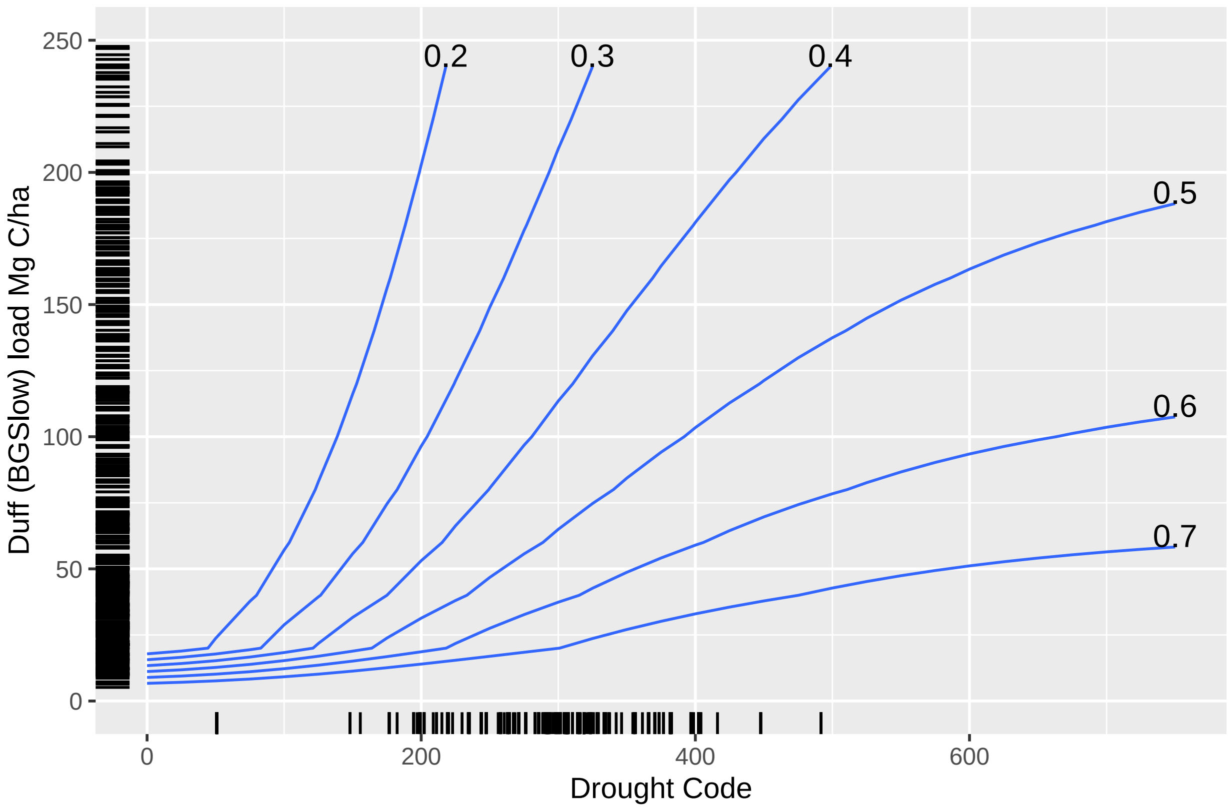


With the parameter constrained NLS fitting, the proportional consumption model for the forest floor has a leave-one-out (conducted at the fire-level, not plot) cross validated r2 of ###, and a Mean Percent Error of ###%

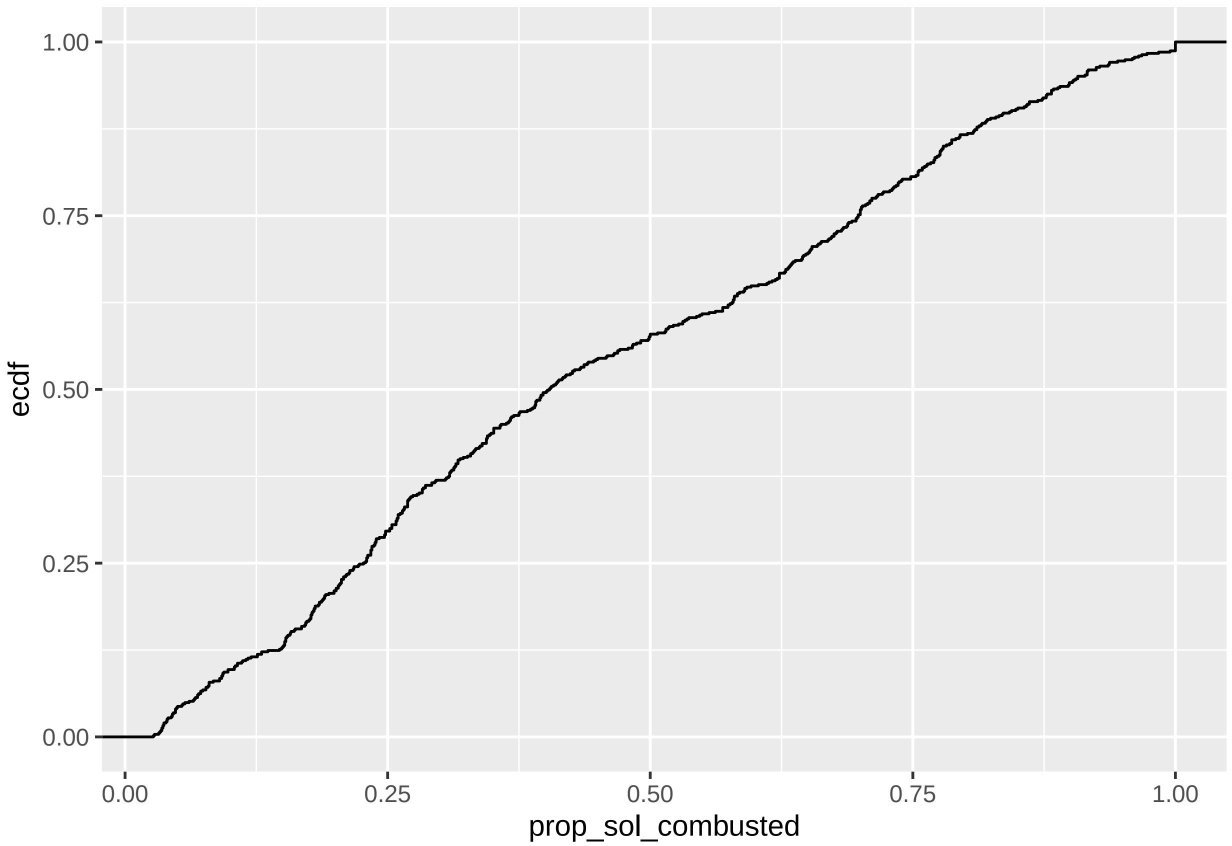
```
## Scale for y is already present.
## Adding another scale for y, which will replace the existing scale.
## Scale for y is already present.
## Adding another scale for y, which will replace the existing scale.
## Scale for x is already present.
## Adding another scale for x, which will replace the existing scale.
```



Across the entire parameter space of Drought Code and BGSlow pool size, the following isolines of proportional consumption in the model can be plotted:



Isoline contours of equal organic soil layer consumption fraction as a function of Drought Code and the orgar



7.0.1 Boreal Cordillera modelling

For the Boreal Cordillera, a simple linear model on the logit-transformed data was found to be the best performing model for estimating soil organic consumption proportion:

$$logit\left(\frac{FFFC}{FFFL}\right) = (0.00257 * DC) + (-0.54 * log_e(BGSlow)) + 2.17 \tag{14}$$

Despite the presence of a fixed intercept term, the strong inverse dependence on the natural logarithm of the BGSlow pool size (FFFL) results in zero proportional consumption when Drought Code is equal to zero.

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

8.0.1 (Currently not running, needs model update)

9 Appendix ###: DM template (can delete in final draft)

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:

Table 9. Example of stored fire disturbance matrix precursor variable information

Ecozone	Pool	Plain.Language.Name	Variable.Name	Value	SeverityClass	InterimValue	Notes
AM	AGFastDOM	Woody Debris Portion of AGFastDOM	CWD.frac.of.AGFastDOM	0.5		TRUE	
BC	AGFastDOM	Woody Debris Portion of AGFastDOM	CWD.frac.of.AGFastDOM	0.5		TRUE	
BP	AGFastDOM	Woody Debris Portion of AGFastDOM	CWD.frac.of.AGFastDOM	0.5		TRUE	
BSW	AGFastDOM	Woody Debris Portion of AGFastDOM	CWD.frac.of.AGFastDOM	0.5		TRUE	
BSE	AGFastDOM	Woody Debris Portion of AGFastDOM	CWD.frac.of.AGFastDOM	0.5		TRUE	
HP	AGFastDOM	Woody Debris Portion of AGFastDOM	CWD.frac.of.AGFastDOM	0.5		TRUE	

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 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 10. Sample of disturbance matrix data file

Ecozone	FluxID	Source	Sink	ProcessSynonym	Phase	CORefFluxID	Pseudocode	Notes	SeverityClass	Value	InterimValue
BSW	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers			1-mortality rate	Ellen provides	Low	1.0	TRUE
TP	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers			1-mortality rate	Ellen provides	Low	1.0	TRUE
TSW	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers			1-mortality rate	Ellen provides	Low	0.9	TRUE
BP	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers			1-mortality rate	Ellen provides	Low	1.0	TRUE
BC	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers			1-mortality rate	Ellen provides	Low	1.0	TRUE
BSE	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers			1-mortality rate	Ellen provides	Low	1.0	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).

10 Appendix D: Representative photos

Photos of: (1) partial litter consumption; (2) partial vs full duff consumption; (3) mortality but not consumption of understory trees with live overstory; (4) mortality but not consumption of overstory trees; (5) mixedwood severity example showing consumption of broadleaf foliage; (6) woody debris consumption; (7) snag preferential consumption relative to little to no bole consumption in live trees

Give lat/long, year, ecozone, severity class, and leading spp for each photo, maybe other relevant metrics? From some of the experimental fires mostly??

11 Appendix E: List of Resprouting Hardwoods of Canada

Alnus spp. Arbutus men. Betula all. Betula pap. Betula pop. Fraxinus ame. Fraxinus nig. Fraxinus pen. Populus bal. Populus gra. Populus tre. Populus tri. Quercus spp. Salix spp.

. This article was produced from an RMarkdown document with underlying data, available at https://github.com/nrcan-cfs-fire/FireDMs

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

Regarding figures and tables in appendices, the following two options are possible depending on your general handling of figures and tables in the manuscript environment:

A1 Option 1

If you sorted all figures and tables into the sections of the text, please also sort the appendix figures and appendix tables into the respective appendix sections. They will be correctly named automatically.

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If you put all figures after the reference list, please insert appendix tables and figures after the normal tables and figures.

To rename them correctly to A1, A2, etc., please add the following commands in front of them: `\appendixfigures` needs to be added in front of appendix figures `\appendixtables` needs to be added in front of appendix tables

Please add `\clearpage` between each table and/or figure. Further guidelines on figures and tables can be found below.

. Thompson and Whitman contributed to the concept and code design with the assistance of Hanes, Hudson

. The authors declare no competing interests.

. The algorithm and results presented only apply to boreal and temperate forest ecosystems where sufficient ground plots of fire severity are available. As a data-driven model, this framework is not suitable for other ecosystems nor agricultural or forestry biomass burning practices.

. Thanks to (insert names here)

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