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

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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. Compared to the baseline high severity-only representation, this mixed severity modelling framework changes modelled total Carbon flux to the atmosphere by [###]%, with the largest changes in [pool]. Per fire energy release rates as detected by satellite yield a favourable rank correlation with this severity-only method, and regional estimates of atmospheric CO release by satellite compare favourably to outputs from this severity-driven model.

1 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).

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 matrice 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.

Table 1. 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

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 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 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 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 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 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 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 (!ref). 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.

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

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 this scheme, we utilize the Forest Floor Fuel Consumption (FFFC) model of (de Groot et al., 2009), modified to only account for fuel horizons below the litter layer:

$$FFFC = 0.016872DC^{0.71}(FFFL - LL)^{0.671} - LL \tag{1}$$

where DC is the Fire Weather Index Drought Code and FFFL is the Forest Floor Fuel Load (with ecozone averages given in (Letang and de Groot, 2012) or site-level data). LL is the Litter Load, and is typically on the order of $0.2\,\mathrm{kg\,m^{-2}}$ 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 (see previous section). 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 is used to provide representative values. Specifically, a median Drought Code of detected fire hotspots in Canada from 2003-2021 using the

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

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:

Little data is available on the fraction of woody debris consumption alongside fire severity measurements. Coarse woody debris of overstory stems that makes up the majority of woody debris biomass in Canada's boreal and temperate forests (!ref), with its moisture and consumption patterns largely follows the moisture regime of the Drought Code (McAlpine, 1995). As a result, in this modelling framework, the proportion of woody debris consumption (!!give diameter range of Med DOM) is assumed proportional to that of the duff consumption given in the equation above.

2.7 Drivers of C losses in the tree canopy

2.7.1 Overstory tree mortality and consumption

Though numerous process-driven tree mortality models are present and show significant skill in predicting tree mortality based on fire behaviour (i.e. flame length, rate of spread) (!ref FOFEM, Johnson etc), since the driving data in this model is satellite-derived fire severity over the landscape scale, fire behaviour metrics such as flame length 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:

And since large-diameter, live trees killed by fire do not experience significant live stemwood consumption, the entirity of the live stemwood biomass pool that is killed is transferred to the snag pool.

Table 4. 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

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 the assumption that any partial crown consumption is likely sufficient to result in mortality (!ref?). From field studies (!Ellen to provide details here. . . .) , the following ecozone-specific CFB values are found:

A major distinction is made between softwood and hardwood trees, where in Canada's boreal forests, a large fraction of hardwood trees (specifically of the genii Populous and Betula) are able to resprout even when the main stem has been killed by an intense forest fire (!ref). Accordingly, the root mortality rates differ greatly between softwoods and hardwoods. Concurrently, the fraction of fine roots contained within the combustible forest floor layers can be a majority of the fine root biomass, and burns alongside the organic soils. As a result, the calculation for softwood fine root consumption and mortality are as follows, using Softwood as an example:

$$SWFineRootConsump = SW.Mort \times SW.Prop.Fine.Root.duff \times Duff.Consump.Fract \tag{2}$$

$$SWFineRootMort.AG = SW.Mort \times SW.Prop.Fine.Root.duff \times (1 - Duff.Consump.Fract) \times (1 - ReSproutFactor) SWFine \tag{3}$$

Table 5. Softwood crown fraction burned by ecozone, as dervied from median values from field studies

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

2.7.2 Understory tree mortality and consumption

Foliage, then roots

2.7.3 Snag consumption

2.7.4 Other biomass pools: stumps and bark

2.8 Construction fire disturbance matrices

3 Results

3.1 2021 Fires in British Columbia, Canada

Give quick summary here, show overview map of all the fires, and also an example of the GCBM biomass pools and also severity classes on a fire or two from Ellen

Then compare old vs new fire DM scheme for individual fires as a biplot

Then show sum of FRP per fire (GOES) as compared to our severity-based scheme here

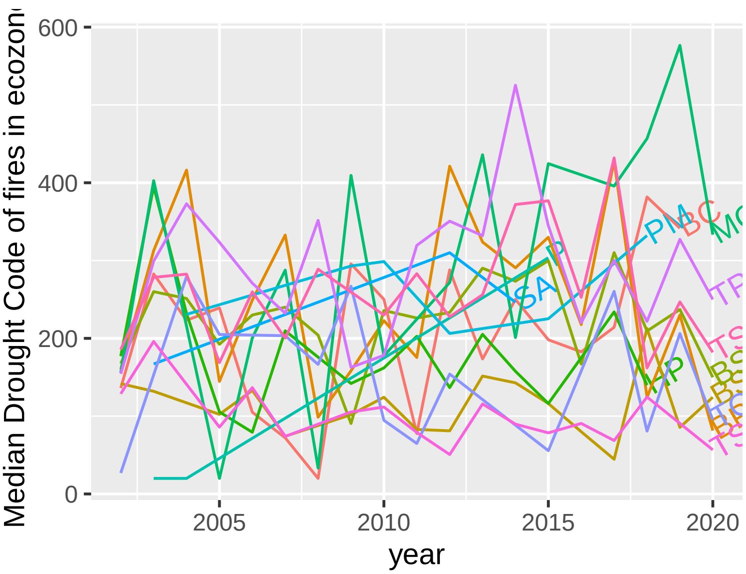
MOPITT?

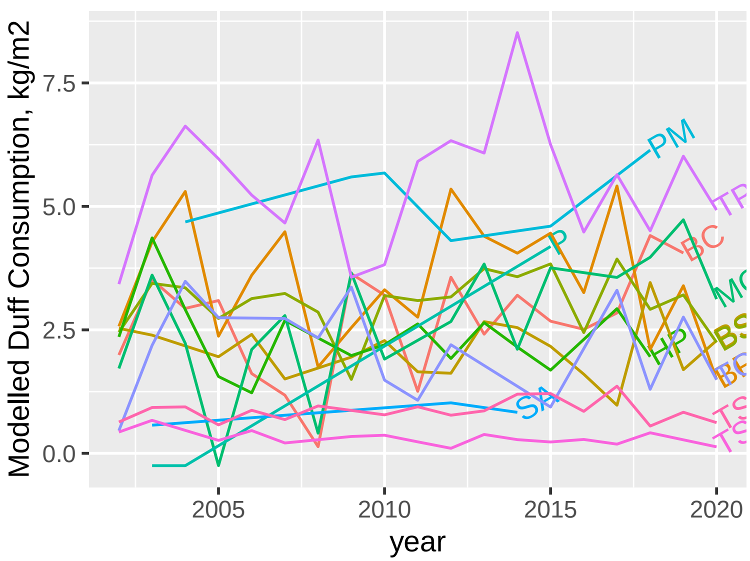
4 Conclusions

The conclusion goes here.

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

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





7 Appendix C: 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:

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.

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).

8 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 consumpotion in live trees

. 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.

A2 Option 2

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.

. 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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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	CO2	Crown Fraction Burned
Softwood Foliage	CH4	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	CO2	Proportional Combustion sum of branches, stumps, small trees and bark
Softwood Other	CH4	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	CO2	Understory Conifer consumption rate
Softwood Submerchantable	CH4	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	CO2	Fine roots combusted alongside duff
Softwood Fine Roots	CH4	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	CO2	Crown Fraction Burned
Hardwood Foliage	CH4	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	CO2	Proportional Combustion sum of branches, stumps, small trees and bark
Hardwood Other	CH4	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	CO2	Understory Broadleaf consumption rate
Hardwood Submerchantable	CH4	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	CO2	Fine roots combusted alongside duff
Hardwood Fine Roots	CH4	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

Table 6. 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		TRUE	
AM	Branch	Hardwood small branch fraction of total branchwood	HW.SmBranch.frac.of.tot.BW	0.5		TRUE	
AM	Other	Softwood branchwood as portion of total "other" pool	SW.BW.frac.of.other	0.4		TRUE	
AM	Other	Hardwood branchwood as portion of total "other" pool	HW.BW.frac.of.other	0.4		TRUE	
AM	Other	Hardwood Bark as portion of "other" pool	HW.bark.frac.of.other	0.1		TRUE	
AM	Other	Softwood Bark as portion of "other" pool	SW.bark.frac.of.other	0.1		TRUE	

Table 7. 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	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
BSW	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers	1-mortality rate	Ellen provides	Low	1.0	TRUE
BP	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers	1-mortality rate	Ellen provides	Low	1.0	TRUE
P	1	Softwood Merchantable	Softwood Merchantable	Survival rate of large conifers	1-mortality rate	Ellen provides	Low	1.0	TRUE