Mountain pine beetle and forest carbon feedback to climate change

W.A. Kurz, C.C. Dymond, G. Stinson, G. J. Rampley, E.T. Neilson, A. Carroll, T. Ebata, and L. Safranyik.

Supplementary Information

Forest ecosystem model description and parameters

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) is an empirically driven, stand- and landscape-level model for the simulation of forest carbon (C) dynamics. Earlier versions of the model were described by Kurz et al.[1] and by Kurz and Apps[2]. The current version of the model builds upon the functionality of CBM-CFS2, and is the core model used in Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS)[3].

Stand-level C dynamics are represented in the CBM-CFS3 using a system of pools that allow the model to represent key ecological processes and that allow users to compare estimates of stocks with field measurements. Each forest stand is represented by 21 C pools: 5 softwood biomass pools, 5 hardwood biomass pools, 2 softwood snag pools, 2 hardwood snag pools, 4 additional aboveground dead organic matter (DOM) pools, and 3 belowground DOM and soil C pools. Aboveground biomass pools are estimated from merchantable volume using a system of regional and species-specific volume to biomass conversion equations[4]. Belowground biomass is predicted from aboveground biomass using stand-level regression equations for softwood and hardwood species[5]. Tree bark is accounted for in each structural component. Each biomass C pool is assigned forest-type and ecozone-specific litterfall and turnover rates.

CBM-CFS3 simulates the annual changes in the C stocks of each pool that occur due to growth, litterfall and turnover, decomposition, natural disturbances, and forest management. The growth module simulates net uptake of C from the atmosphere, i.e. net primary production (NPP), but does not estimate gross primary production or autotrophic respiration. C is transferred to DOM through annual turnover and litterfall rates or through event-driven disturbances. The DOM pools are distinguished by the type of biomass they receive, and by unique decay and C transfer rates. Decomposition is simulated using temperature-dependent, pool-specific decay processes which transfer most of the decay losses to the atmosphere and a portion to a slow C pool.

Disturbances can contribute to C transfers and the loss of C from the forest ecosystem. Harvesting causes transfers to the forest product sector that are reported as ecosystem losses in the model output. Gaseous emissions, such as from a fire, are transferred to the atmosphere as CO_2, CH_4 and CO and are represented as ecosystem losses in the model output. Disturbances can affect stand age and the subsequent biomass and DOM C dynamics in the disturbed stand.

The simulation of initial conditions for soil and DOM C pools is generated by a spin-up procedure that establishes DOM pool sizes based on disturbance history before the beginning of the simulation[2]. Parameters have been updated for decomposition, fire impacts[6], insect impacts and climate. The model and all ecological parameters are freely available on the internet at carbon.cfs.nrcan.gc.ca.

CBM-CFS3 was designed to meet the requirements for an operational tool[7]. While the CBM-CFS2 was a research tool that provided no tools or support for simulation design or input/output file processing, the CBM-CFS3 has a graphical user interface and includes data pre- and post-processing tools and a detailed User's Guide[8]. Furthermore, the spatial resolution of the model has been greatly increased, allowing the explicit simulation of millions of stands in annual time steps. When used in a monitoring role to assess past changes in C stocks, the model can be spatially explicit and represent each polygon in a forest inventory with a corresponding database record. Flexibility for modelling growth, management activities, disturbances and post-disturbance dynamics has also been improved relative to CBM-CFS2.

In the CBM-CFS3, disturbances and forest management activities cause transfers of C between pools and removals from the ecosystem. In this study, fires were simulated as stand-replacing events. A portion of foliage and aboveground DOM pools were consumed, all remaining biomass was killed, and standing snags were transferred to litter and coarse woody debris pools. Fire C transfer coefficients are provided in Table S1. Harvest events were simulated as stand-replacing clearcut events, with 85% of merchantable stemwood and 72% of snag stemwood C transferred out of the ecosystem to the forest products sector. The rest of the C in biomass pools was transferred to DOM pools. Harvest C transfer coefficients are provided in Table S2. Transfers of C from the ecosystem to the forest products sector were reported by the model as losses from the ecosystem, in accordance with current international C accounting guidelines[9] and good practice guidance provided by the Intergovernmental Panel on Climate Change (IPCC)[10]. Following stand-replacing disturbance events, disturbed stands were regrown from age zero on the original growth curve.

Mountain pine beetle impacts were simulated as partial-mortality events which killed a portion of softwood (host) biomass pools. The beetle impacts were parameterized by translating the damage classes reported in the aerial overview survey into percent of crown killed and then into percent of softwood biomass killed for use in the CBM-CFS3 (Table S3). The stand mortality classes were 5%, 10%, 30% or 50% per year (Table S4). These assignments take into consideration the nature of the aerial survey data, the stand structure of the infested stands, and the tendency of the beetle to infest larger diameter host trees first when attacking a stand. First, the area distribution of damage within a damage class tends to be greater towards the lower end of the range. Second, lighter damage tends to precede more severe damage during multi-year infestations, with larger diameter trees being attacked first. Finally, we calibrated the damage classes such that multi-year outbreaks in the model would result in the same cumulative mortality levels that are observed in the field following beetle outbreak. Even in the most severe cases, it is rare for mountain pine beetle to kill 100% of the pine component of infested stands.

We validated our calibrations of beetle impact for the portion of the forest subject to commercial timber harvest against estimates produced by the British Columbia Ministry of Forests and Range (MoFR) using a different modelling approach[11]. MoFR estimates of the loss of merchantable wood volume resulting from the beetle outbreak were very similar to our estimates of wood volume loss (Figure S1). MoFR estimates were generated by converting area infested (by severity class) directly into merchantable volume impacts while our estimates were generated by converting area infested into biomass C impacts. Our biomass C impact estimates were translated into volume for comparison purposes by assuming a specific gravity of 0.397 g m^{-3} and 0.5 t C t^{-1} biomass for the merchantable stemwood.

Decomposition processes were simulated as the loss of C as gaseous emissions.and the transfer of C between DOM pools. Decay rates determine the amount of organic matter that decomposes in the DOM pools every year. Proportions determine the amount of C in decayed material that is released to the atmosphere (P_{atm}) or transferred to a more stable DOM pool (P_{trans}) with (P_{atm}+

P_{trans} =1) (Table S5). The decay rates vary with mean annual temperature (MAT). We determined the average MAT for each analysis unit by geographic intersection with 30 arc-second gridded 1961-1990 climate normals.

Input data

The British Columbia Ministry of Forests and Range (MoFR) supplied the forest inventory and growth curve data used in this study. We assigned almost 700,000 forest stands to 86 spatial analysis units that represented the administrative and ecological variability in the study area. These were the same data that the MoFR uses for timber supply reviews, but were supplemented with additional information describing forest lands outside of the timber harvesting landbase (e.g. parks, dedicated wildlife habitat areas, riparian buffer zones, physically inoperable lands, etc.) to complete the inventory of all forest lands in the study area.

Spatially explicit area burned data were extracted from the Canadian Large Fire Database[12] and the Canadian Wildland Fire Information System[13] for 2000-2005. Spatially explicit data on areas infested by mountain pine beetle were extracted from MoFR annual forest health surveys[14] for 2000-2006. Fire and beetle disturbance datasets were geographically intersected with our 86 sptial analysis units in a Geographic Information System and disturbance target areas were calculated for each disturbance type by spatial analysis unit and year for use in the CBM-CFS3 simulations. The MoFR also provided statistics on historical harvest, base projected harvest and additional projected harvest response for each management unit in the study area (Figure S2). A series of disturbance eligibility rules and sorting algorithms were used in the CBM-CFS3 to select stands for disturbance from the forest inventory. Stands affected by fire were selected at random. Mountain pine beetle host stands were defined as pine-leading between 40 and 250 years old, with the oldest stands selected first during the infestation. In the most severely infested part of the study area, spruce-leading stands (which contain a significant pine component in the study area) and stands as young as 20 years were also eligible for beetle disturbance. For areas with severe or very severe mortality classes, the stand selection rules further specified that only stands with infestation in prior years were eligible for beetle disturbance. The host characteristics and stand selection algorithms were developed based on observed and published beetle behaviour[15,16]. CBM-CFS3 selected stands for base harvest by sorting for the highest amount of C in the merchantable stemwood pool. For the additional harvest, the model selected stands based on the greatest amount of available C in the snag (standing dead tree) pools. These simulation rules were developed in consultation with MoFR experts to ensure they adequately reflected current forestry operations.

We projected the area infested by mountain pine beetle from 2007-2020 using random draws from regionally calibrated probability distributions of outbreak area and duration. The probability distributions were defined using interpretations of (i) spatial and temporal outbreak dynamics during 1960-2006 (Figure S3), (ii) mortality and host statistics for the early part of the current outbreak, (iii) status of remaining host, and (iv) expert judgment. The annual area infested and severity of impact were modelled as temporally and spatially autocorrelated; area infested in a given year affected the probability and size of the area infested in the next year.

We constructed 100 Monte Carlo projections of future years of the beetle outbreak using a number of parameters defined for five modelling regions (Figure S4). The areas annually infested by beetle in each region were single time series, drawn at random using regional parameters (Table S4). Future area infested by low, moderate, severe and very severe mortality levels was derived by describing for each region: (i) the range of possible outbreak durations in years, (ii) the total area available as host, (iii) the area infested to date during the current outbreak and during historical outbreaks, and (iv) the rate of expansion and contraction of area infested (outbreak shape). The outbreak duration is the period of time in the outbreak cycle during which the beetle population is high enough to cause visible damage to host trees. This damage is usually assessed during forest health aerial overview surveys and can be used to estimate host mortality. Spatially correlated regions had similar parameters for projecting the remaining duration of the ongoing outbreak. The total area affected by an outbreak was the sum of annual area affected by an outbreak. The duration and total area parameters are described using probability density functions. The distributions to model these parameters were restricted to simple distributions that require few data: uniform, triangular and normal[17]. For the mountain pine beetle outbreak, the parameters were extended beyond the historical data to reflect the unprecedented infestation that is currently underway and the entomologists' best estimates of the future trajectories of this outbreak.

Fire projections of future area burned were derived from regionally calibrated probability density functions parameterised using historical fire statistics for the period 1959-1999. The fire modelling regions were defined based on previous analysis of fire occurrence, area burned and severity. The historical record of annual area burned in each stratum was extracted from the Canadian Large Fire Database, which contains spatially explicit information on all fires greater than 200 ha in size from 1959 to 1999 (Figure S5).

To format the time series of annual area burned into an observed cumulative probability distribution, we defined 100 equally sized bins from zero to the maximum annual area burned in the region. The frequency (i.e. number of years) was assigned to each bin and these were then converted into the proportion of all years. We used the software BestFit™ version 4.5 (Palisade Corporation, Newfield, New York) to fit probability density functions to the empirical distributions. BestFit™ chooses from up to twenty-eight probability distribution functions, and selects the appropriate parameters for that distribution using maximum-likelihood estimators. We chose probability density functions region by region based on evaluation of the representation of large, low probability events and the overall RMS error (Table S7). The probability of an annual area burned greater than the largest area in the historical record in the region under consideration was constrained to between 1% and 2%. That is, if the distribution had a greater than 2% probability of generating an area burned greater than the maximum observed, it was rejected (even if it was a valid fit statistically and had a low RMS error). Similarly, if a distribution had a less than 1% probability of generating an area burned greater than the maximum observed it was also rejected. We also truncated the projected maximum area burned to twice the historical maximum. Our preliminary investigation indicated that the assumptions made about the magnitude of projected maximum had significant impacts on the fire cycle (i.e. the number of years that it takes to burn an area equal in size to the reference area). Truncating the maximum annual area burned at twice the maximum observed in the historical record maintained the historical fire cycle in repeated, randomly generated projections.

Table S1. Fire impacts as defined for this study by the proportion of carbon pool transferred to a new pool or emitted directly to the atmosphere as CO_2, CO or CH_4.

Pre-disturbance pool	Post-disturbance pool	Proportion
Hardwood foliage	CH4	0.010
	CO	0.090
	CO2	0.900
Hardwood merchantable	Hardwood stem snag	1.000
Hardwood other wood	Hardwood branch snag	1.000
Hardwood fine roots	Aboveground very fast DOM	0.036
	CH4	0.005
	CO	0.042
	CO2	0.422
	Belowground very fast soil	0.500
Hardwood coarse roots	Aboveground fast soil	0.500
	Belowground fast soil	0.500
Hardwood stem snag	Medium DOM	1.000
Hardwood branch snag	Aboveground fast soil	1.000
Softwood foliage	CH4	0.010
	CO	0.090
	CO2	0.900
Softwood merchantable	Softwood stem snag	1.000
Softwood other wood	CO	0.025
	CO2	0.225
	Softwood branch snag	0.750
Softwood fine roots	Aboveground very fast DOM	0.041
	CH4	0.005
	CO	0.041
	CO2	0.413
	Belowground very fast DOM	0.500
Softwood coarse roots	Aboveground fast soil	0.500
	Belowground fast soil	0.500
Softwood stem snag	Medium DOM	1.000
Softwood branch snag	Aboveground fast soil	1.000
Medium DOM	CH4	0.009
	CO	0.085
	CO2	0.853
	Unaffected portion	0.052
Aboveground very fast DOM	CH4	0.010
	CO	0.090
	CO2	0.900
Aboveground fast soil	CH4	0.010
	CO	0.088
	CO2	0.882
	Unaffected portion	0.020
Aboveground slow soil	CH4	0.009
	CO	0.083
	CO2	0.826
	Unaffected portion	0.082
Belowground very fast DOM	Unaffected portion	1.000
Belowground fast soil	Unaffected portion	1.000
Belowground slow soil	Unaffected portion	1.000

Table S2. Harvest impacts defined for this study by the proportion of carbon pool transferred to a new pool or removed to the forest product sector. Pools not explicitly included in this table are unaffected by harvest events.

pre-disturbance pool	post-disturbance pool	Proportion
Hardwood foliage	Aboveground very fast DOM	1.000
Hardwood merchantable	Forest products sector	0.850
	Medium DOM	0.150
Hardwood other wood	Aboveground fast DOM	1.000
Hardwood fine roots	Aboveground very fast DOM	0.500
	Belowground very fast soil	0.500
Hardwood coarse roots	Aboveground very fast DOM	0.500
	Belowground very fast soil	0.500
Hardwood stem snag	Forest products sector	0.720
	Medium DOM	0.280
Hardwood branch snag	Aboveground fast DOM	1.000
Softwood foliage	Aboveground very fast DOM	1.000
Softwood merchantable	Forest products sector	0.850
	Medium DOM	0.150
Softwood other wood	Aboveground fast DOM	1.000
Softwood fine roots	Aboveground very fast DOM	0.500
	Belowground very fast soil	0.500
Softwood coarse roots	Aboveground fast DOM	0.500
	Belowground fast soil	0.500
Softwood stem snag	Forest products sector	0.720
	Medium DOM	0.280
Softwood branch snag	Aboveground fast DOM	1.000

Table S3. Mountain pine beetle aerial overview survey damage classes are defined by the percent of trees recently killed*. The CBM-CFS3 simulates beetle impacts for each damage class as percent softwood biomass killed per year.

Damage Class	Percent of trees Killed	Percent softwood biomass killed
Trace	<1	not simulated
Light	1-10	5
Moderate	11-30	10
Severe	31-50	30
Very Severe	>50	50

* *Procedures for Landscape-level Forest Health Factor Surveys*
http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/health/gfhs0004.htm#E10E4

Table S4. Mountain pine beetle impacts defined for this study by the proportion of carbon pool transferred to a new pool in CBM-CFS3 for light (L), moderate (M), severe (S) and very severe (VS) damage classes. Pools not explicitly included in this table are unaffected by beetle infestation.

Pre-disturbance pool	Post-disturbance pool	Proportion			
		L	M	S	VS
Softwood foliage	Aboveground very fast DOM	0.050	0.100	0.300	0.500
	Unaffected portion	0.950	0.900	0.700	0.500
Softwood merchantable	Softwood stem snag	0.050	0.100	0.300	0.500
	Unaffected portion	0.950	0.900	0.700	0.500
Softwood other wood	Softwood branch snag	0.050	0.100	0.300	0.500
	Unaffected portion	0.950	0.900	0.700	0.500
Softwood fine roots	Aboveground very fast DOM	0.025	0.050	0.150	0.250
	Belowground very fast soil	0.025	0.050	0.150	0.250
	Unaffected portion	0.950	0.900	0.700	0.500
Softwood coarse roots	Aboveground fast DOM	0.025	0.050	0.150	0.250
	Belowground fast soil	0.025	0.050	0.150	0.250
	Unaffected portion	0.950	0.900	0.700	0.500

Table S5. **P**arameters used to simulate dead organic matter (DOM) dynamics in this study. Decay rates listed are base decay rates for 10^{o}C; all except slow pools have a Q10 of 2; slow pools have a Q10 of 0.9; AG = aboveground, BG = belowground.

DOM Pool	Turnover rate (% of C)	Turnover receiving pool	Decay rate (% of C)	P_{atm}	Decay receiving pool (P_{trans} = 1-P_{atm})
Stem snags	0.032	Medium	0.0187	0.830	AG Slow
Snag branches	0.100	AG Fast	0.0718	0.830	AG Slow
Medium			0.0374	0.830	AG Slow
AG Fast			0.1435	0.830	AG Slow
AG Very fast			0.5000	0.830	AG Slow
AG Slow	0.006	BG Slow	0.0032	1.000	
BG Fast			0.1435	0.830	BG Slow
BG Very fast			0.5000	0.830	BG Slow
BG Slow			0.0032	1.000	

Table S6. Parameters for probability density functions (PDFs) describing different aspects of the mountain pine beetle projections.

Modelling region (see Figure S4)	PDF for Length of Insect Outbreak (years)	PDF for Total Area of Insect Outbreak (percent of host area)	Host area (kha)	Start Year of Current Outbreak	Sum of Area from start year to 2006 (kha)
Contiguous host	$f(x)=1/(25-14)$ ^	$f(x)=1/(600-560)$ ^	5,295	1996	14,978
Discontiguous host	$f(x)=1/(25-18)$ ^	$f(x)=1/(750-400)$ ^	5,186	1999	9,527
Patchy host (NW)	$f(x)=2(x-14)/(33)$ * when $x\leq 17$ $f(x)=2(25-x)/(88)$ * when $x>17$	$f(x)=1/(100-50)$ ^	132	2001	17
Patchy host (SE)	$f(x)=2(x-14)/(22)$ * when $x\leq 16$ $f(x)=2(25-x)/(99)$ * when $x>16$	$f(x)=1/(250-150)$ ^	1,264	2000	475
Climate limited	$f(x)=2(x-8)/(36)$ * when $x\leq 11$ $f(x)=2(20-x)/(108)$ * when $x>11$	$f(x)=1/(200-130)$ ^	1,158	2002	358

* Triangular distribution
$f(x)=2(x-min)/((mode-min)(max-min))$ when $x\leq mode$
$f(x)=2(max-x)/((max-mode)(max-min))$ when $x>mode$
^ Uniform distribution
$f(x)=1/(max-min)$

Table S7. Parameters for annual burned area projections.

Modelling region (see Fig. S4)	PDF for annual area burned (ha)	Max. annual area burned (ha)	Probability of maximum occurring in a random draw
1^	$f(x)=[1/((0.60652)(17857)\Gamma)]\ (x/17857)^{0.60652-1}\ (e^{-x/17857})$	97,687	0.14
2^	$f(x)=[1/((0.1892)(45673)\Gamma)]\ (x/45673)^{0.1892-1}\ (e^{-x/45673})$	226,710	0.03
3*	$f(x)= [(0.2985x^{0.2985-1})/ 1070.3^{0.2985}]\ (e^{-(x/1070.3)\wedge 0.2985})$	130,494	1.51

* Weibull distribution
$f(x)= [(\alpha x^{\alpha-1})/\beta^{\alpha}]\ (e^{-(x/\beta)\wedge\alpha})$
^ Gamma distribution, Γ= Gamma function
$f(x)=[1/(\alpha\beta\Gamma)]\ (x/\beta)^{\alpha-1}\ (e^{-x/\beta})$

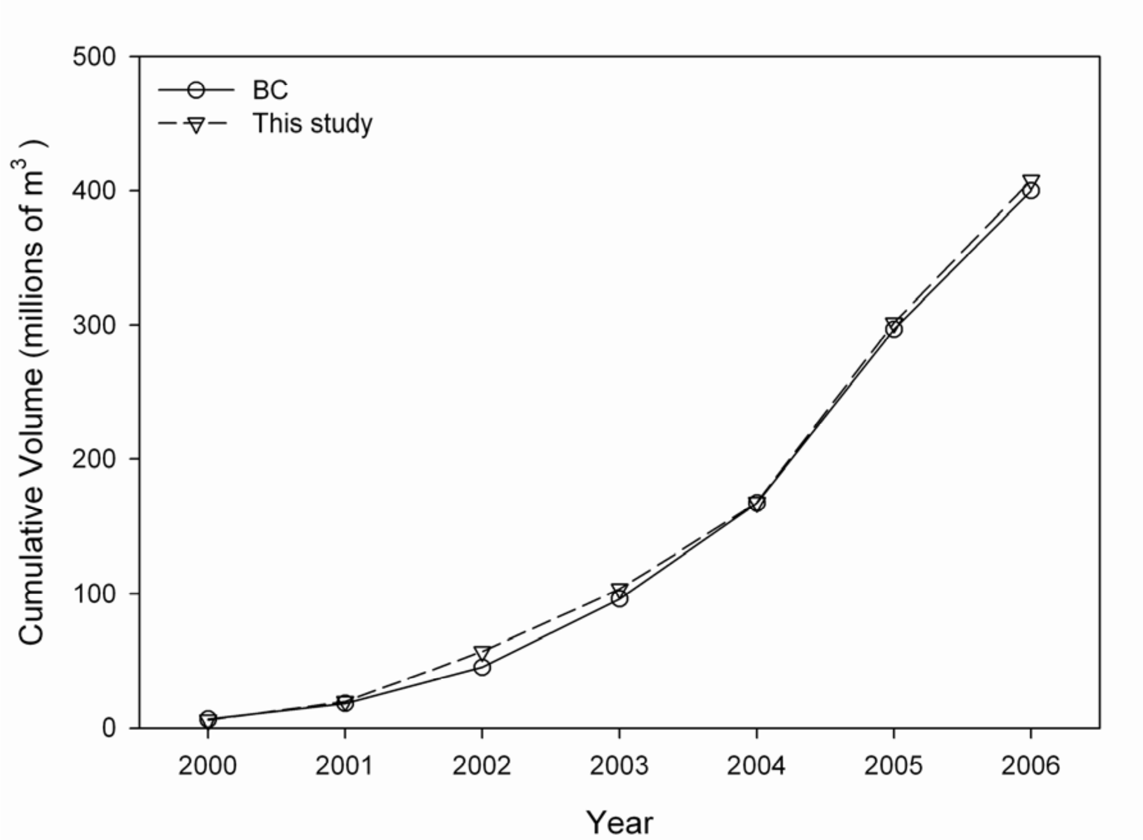

Figure S1. Comparison of our model estimates of cumulative volume killed by the mountain pine beetle against timber volume killed estimates produced using different methods by the British Columbia Ministry of Forests and Range. This comparison is only for the portion of the study area subject to commercial harvest.

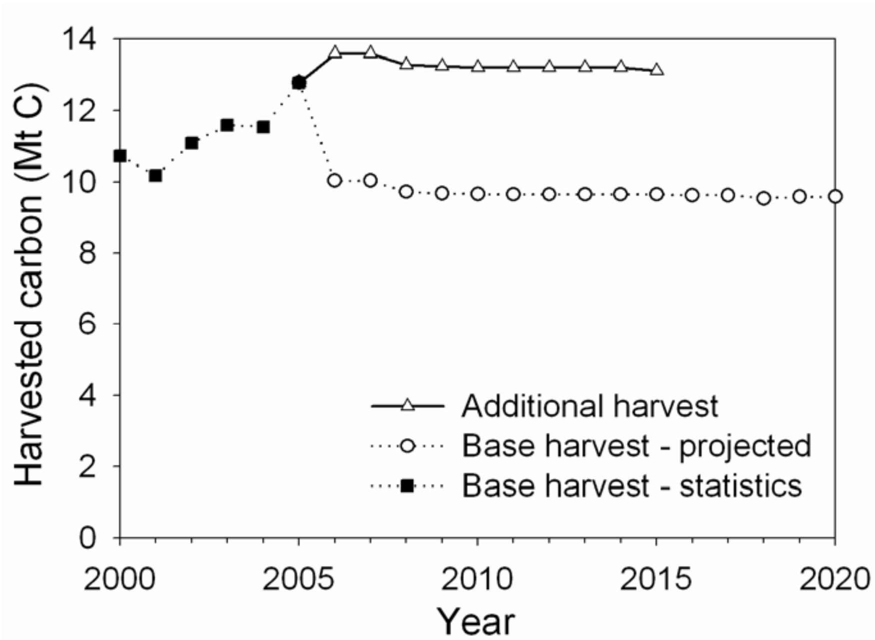

Figure S2. Base harvest statistics used in all simulations and additional harvest in response to the beetle outbreak. Solid squares (2000 – 2005) denote statistics; circles and triangles mark projections (2006-2020) for base harvest and additional harvest, respectively. After 2015, the additional harvest scenario returns to the base harvest level.

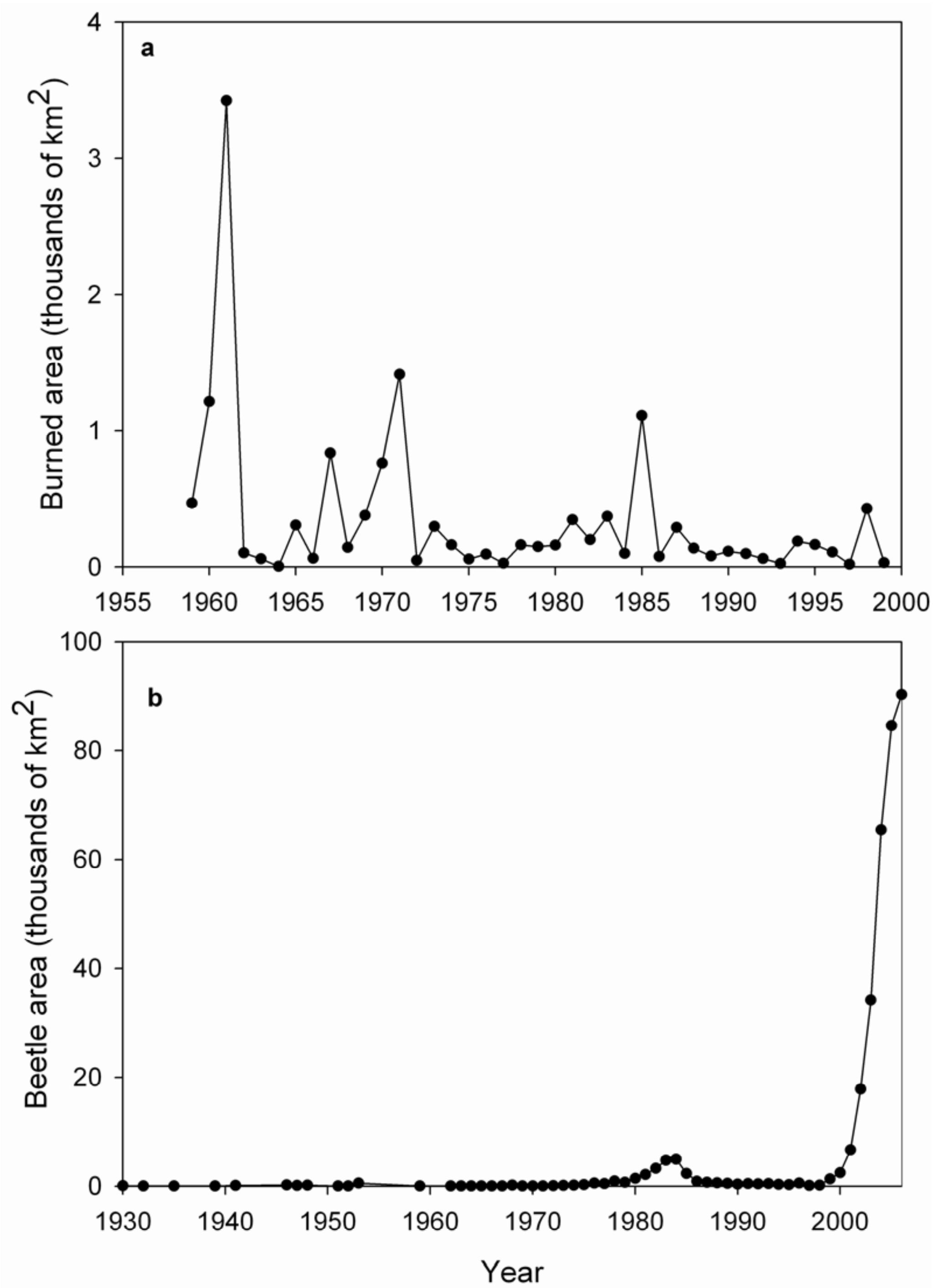

Figure S3. Historical record of area annually burned from Stocks et al. (a) and area infested by mountain pine beetle (b) in British Columbia from Taylor et al.[18]

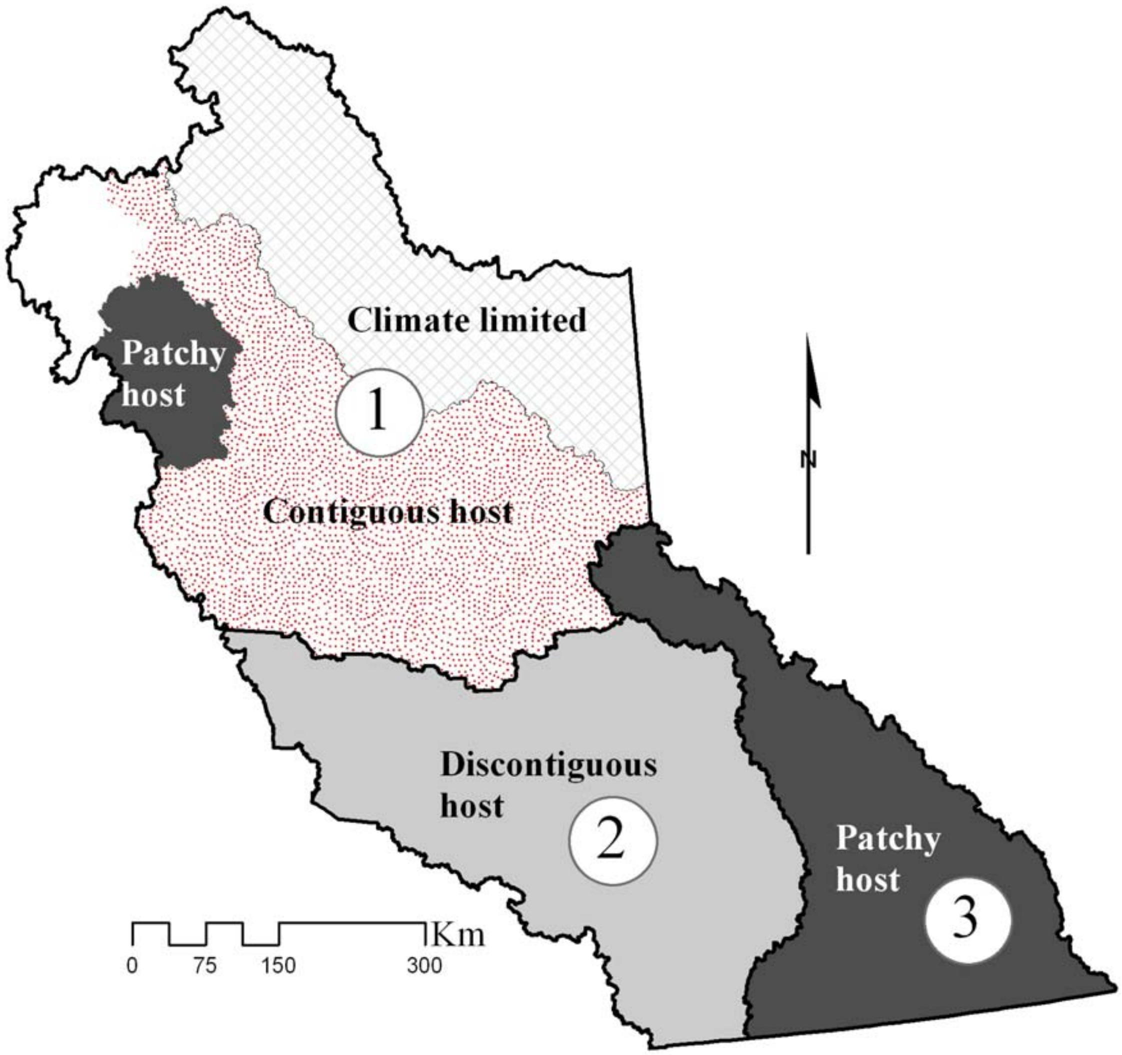

Figure S4. Mountain pine beetle modelling regions (shaded areas) were defined based on spatial distribution of host on the landscape and on climate characteristics. Contiguous host resulted in most severe infestations with patchy host providing less than optimal forest conditions for infestation. Climate limited host area is characterized by colder winters and less than optimal climatic conditions. Discontiguous host area had suitable climatic conditions, but with less than optimal host configuration on the landscape, interspersed with areas of non-host species. The study area also contained three discrete fire modelling regions (1, 2, and 3), delineated by thick black borders. The northwest corner of fire region (1) (white) contained unsuitable host and climate conditions for beetle. Fire area 1 overlapped with three beetle modelling regions, while each of the other two fire regions overlapped with only one beetle modelling region.

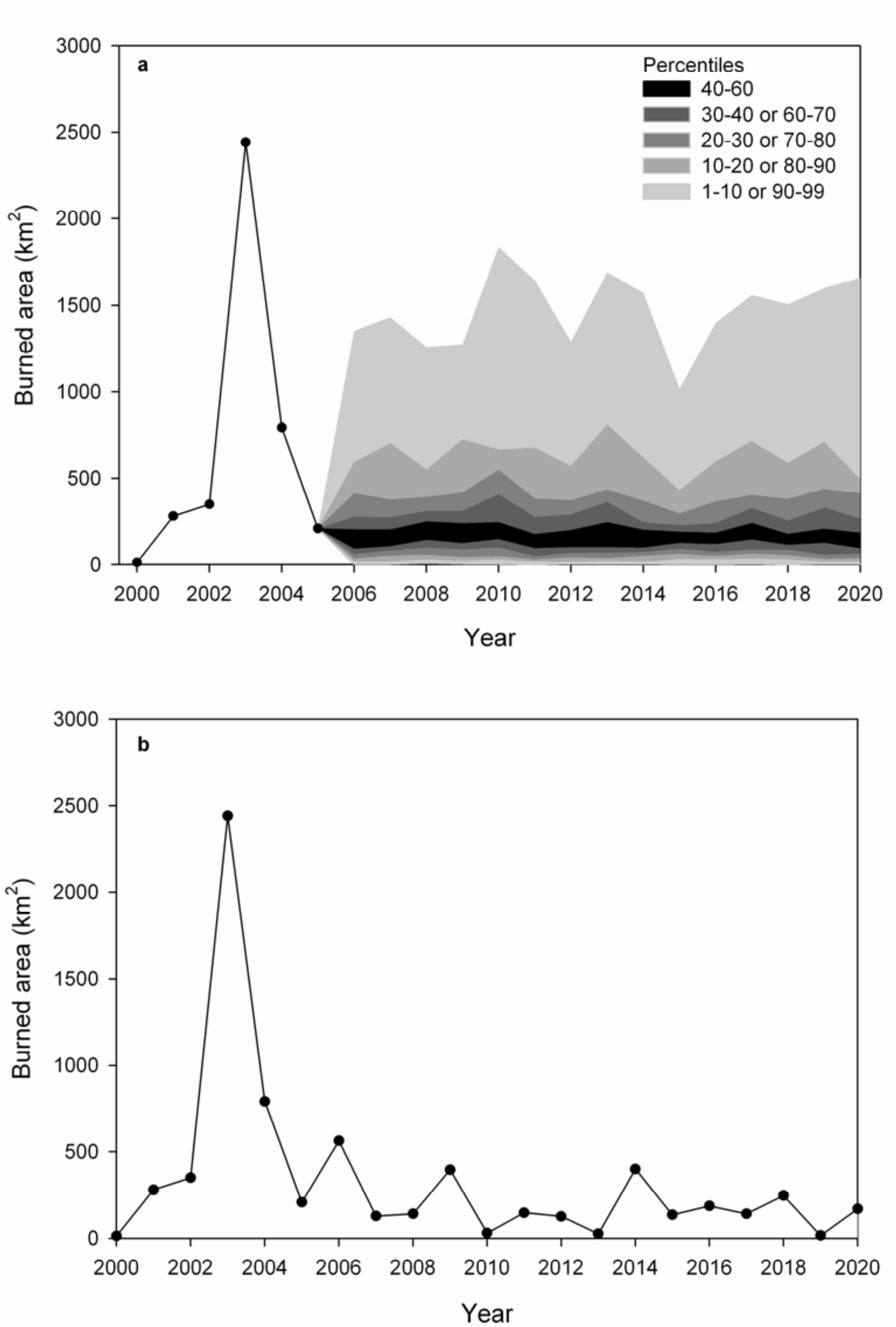

Figure S5. (a) percentiles from 100 random draws from three fire probability density functions based on historic data from 1959 - 1999. Solid circles (2000 – 2005) denote statistics. (b) Area disturbed by fire used in beetle scenario analysis.

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