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Simulated western spruce budworm defoliation reduces torching and crowning potential: a sensitivity analysis using a physics-based fire model

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Abstract. The widespread, native defoliator western spruce budworm (*Choristoneura occidentalis* Freeman) reduces canopy fuels, which might affect the potential for surface fires to torch (ignite the crowns of individual trees) or crown (spread between tree crowns). However, the effects of defoliation on fire behaviour are poorly understood. We used a physics-based fire model to examine the effects of defoliation and three aspects of how the phenomenon is represented in the model (the spatial distribution of defoliation within tree crowns, potential branchwood drying and model resolution). Our simulations suggest that fire intensity and crowning are reduced with increasing defoliation compared with un-defoliated trees, regardless of within-crown fuel density, but torching is only reduced with decreasing crown fuel density. A greater surface fire intensity was required to ignite the crown of a defoliated compared with an un-defoliated tree of the same crown base height. The effects of defoliation were somewhat mitigated by canopy fuel heterogeneity and potential branchwood drying, but these effects, as well as computational cell size, were less pronounced than the effect of defoliation itself on fire intensity. Our study suggests that areas heavily defoliated by western spruce budworm may inhibit the spread of crown fires and promote non-lethal surface fires.

Additional keywords: canopy bulk density, CFD, Computational Fluid Dynamic model, critical surface fire intensity, Douglas-fir, fire behaviour, fuel moisture, surface fire intensity, WFDS, wildland–urban interface fire dynamic simulator.

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Introduction

Western spruce budworm (*Choristoneura occidentalis* Freeman), a North American lepidopteran, is one of the most damaging defoliating insects in the forests of western North America (Fellin and Dewey 1982; Wickman 1992). Widespread, regionally synchronous outbreaks have occurred for centuries (Anderson *et al.* 1987; Hadley and Veblen 1993; Swetnam and Lynch 1993; Swetnam *et al.* 1995; Ryerson *et al.* 2003; Campbell *et al.* 2006), with average outbreak durations of 10 to 14 years (Swetnam and Lynch 1989, 1993; Swetnam *et al.* 1995; Ryerson *et al.* 2003). In 1986, the peak of the last major outbreak, western spruce budworm defoliation affected more than 5×10^6 ha (13×10^6 acres) in the US (Hofacker *et al.* 1989) and the next widespread outbreak may be starting (Man 2009).

Over the last several decades, land use and changing climate have altered natural disturbance regimes in western North America. The severity, duration, frequency and synchrony of outbreaks of western spruce budworm has increased in conjunction with an increasing density of host species (Anderson *et al.* 1987; Swetnam and Lynch 1989, 1993; Swetnam *et al.* 1995). Fire has similarly increased in spatial extent and, in some cases, severity (Arno 2000; Westerling *et al.* 2006; Littell *et al.* 2009; Miller *et al.* 2009). The rate and magnitude of these changes will likely intensify for both disturbance types as climate changes over the next century (Williams and Liebhold 1995; McKenzie *et al.* 2011). Understanding how these two forest disturbances interact, especially how fire behaviour changes during and after outbreaks, is highly relevant for fire and forest managers.

Interactions of insects and fire

By feeding on conifer needles, caterpillars of the western spruce budworm defoliate tree crowns, leading to decreased growth and scattered mortality of host trees over large areas during outbreaks. They defoliate a variety of conifers, but prefer Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), grand fir (*Abies grandis* (Doug. ex D. Don) Lindl.) and white fir (*Abies concolor* (Gord. and Glend.) Lindl. ex Hildebr.). Western spruce budworms emerge from silken tents (hibernacula) in late spring and burrow into the buds of host trees, preferentially feeding on new foliage (Fellin and Dewey 1982; Redak and Cates 1984; Kolb *et al.* 1999; Chen *et al.* 2003). In subsequent years, the tree flushes using stored carbon. New foliage is then available to the larvae (Brookes *et al.* 1987), so that each year's growth can expand an outer zone of bare, defoliated branches, whereas an inner zone of older foliage remains untouched except in severe infestations (Fig. 1). The effect of western spruce budworm varies with host tree size. Large host trees are relatively less defoliated and are less likely to die whereas small host trees are more heavily defoliated and tend to die within a few years (Alfaro *et al.* 1982).

Insect outbreaks, including those of western spruce budworm, have been thought to increase potential forest fire severity or probability of occurrence, or both, by increasing dead fuel loads (Schowalter 1986; Stocks 1987; McCullough *et al.* 1998; Swetnam and Betancourt 1998; Hummel and Agee 2003; Ryerson *et al.* 2003; Parker *et al.* 2006; Pohl *et al.* 2006) However, most studies have focussed on insects that cause high tree mortality, like mountain pine beetle (*Dendroctonus ponderosae* Hopkins) and eastern spruce budworm (*Choristoneura fumiferana* (Clemens); Stocks 1987; Fleming *et al.* 2002; Jasinski and Payette 2005; Page and Jenkins 2007; Hoffman *et al.* 2012; Jolly *et al.* 2012*a*). In contrast, western spruce budworm causes relatively little tree mortality (Fellin and Dewey 1982; Alfaro and Maclauchlan 1992), outbreaks are not as widespread (Powell 1994; Swetnam *et al.* 1995), and attacked trees retain few dead needles. Thus, the impacts of western spruce budworm on fuel loads and fire behaviour likely differ from other defoliators or bark beetles. Indeed, modern fire and western spruce budworm occurrence are negatively correlated in space and time in British Columbia, Oregon and Washington (Lynch and Moorcroft 2008; Preisler *et al.* 2010). However, these broad-scale correlational studies did not investigate the mechanisms by which western spruce budworm affects fire occurrence or behaviour, mechanisms that are relevant for managing fire in stands currently being defoliated.

Western spruce budworm outbreaks might alter fire behaviour directly or indirectly. Defoliation removes foliage from tree crowns, which could reduce potential torching (ignition of individual tree crowns) or crowning (fire spread between trees). However, the remaining crown fuel might be more flammable if it had a lower moisture content (Fellin and Dewey 1982; Brookes *et al.* 1987; Bulaon and Sturdevant 2006). Fire behaviour could change indirectly, through changes in the environment such as increasing wind speed when defoliation reduces canopy drag, increasing surface fuels due to tree mortality or decreasing surface fuel moisture when defoliation decreases shading. We do not model all of these interacting factors here, but we are examining them in a larger project investigating interactions between forest fires and western spruce budworm across multiple scales of time and space.

Fig. 1. A Douglas-fir defoliated by western spruce budworm.

Modelling fire in stands defoliated by western spruce budworm

Previous examinations of fire and western spruce budworm (Hummel and Agee 2003) employed the most comprehensive stand level fire model available at the time (FFE-FVS; Reinhardt and Crookston 2003). However, this model is not sensitive to the sub-meter scale at which defoliation removes crown fuel (Fig. 1) and its underlying fire modelling framework has significant limitations for crown fire (Cohen *et al.* 2006; Jolly *et al.* 2012*b*), often resulting in under-prediction of crown fire spread rates (Cruz *et al.* 2005; Cruz and Alexander 2010; Alexander and Cruz 2013). We attempt to improve on this effort by using a mechanistic model that allows us to investigate fine-scale changes in crown fuel.

Computational fluid dynamic (CFD) models such as HIGRAD-FIRETEC (Linn 1997; Pimont *et al.* 2009; Linn and Anderson 2012) and the wildland–urban interface fire dynamic simulator (WFDS; Mell *et al.* 2009) provide a new way to look at complex fire and fuel interactions. CFD models solve equations for transport of mass, momentum and energy, simulating the dynamic spread of fire as well as thermal properties of fuels (radiation and degradation), on a three dimensional grid. The capacity of these models to represent individual tree crowns in space, as well as to quantify heat fluxes and fuel consumption within them allows us to simulate the fine scale fuel changes caused by western spruce budworm defoliation. Here, we used WFDS because it can use spatial scales as small as meter to sub-meter which are comparable to scales at which defoliation affects tree crowns.

We used version 5.5.3 of WFDS, which extends the fire dynamic simulator (FDS; McGrattan *et al.* 2010) to vegetative fuels in outdoor environments. Development of WFDS is possible through a collaboration of the US Forest Service and the National Institute of Standards and Technology (NIST). Although WFDS continues to evolve and improve, many studies have demonstrated its sensitivity to detailed and variable fuels (Parsons 2006; Mell *et al.* 2010; Parsons *et al.* 2011; Hoffman *et al.* 2012), and demonstrated its use in prescribed (Mell *et al.* 2005, 2007) and wildand fires (Malangone *et al.* 2012), as well as in laboratory experiments of wildland fuels (Mell *et al.* 2006; Menage *et al.* 2012). Other studies have validated the underlying combustion equations of FDS (Mell *et al.* 1996; Sun and Jenkins 2006; McDermott *et al.* 2010*a*, 2010*b*), including its application to laboratory burning of Douglas-fir trees (Mell *et al.* 2009), a host species for western spruce budworm.

Objective

Our objective was to infer the effects of western spruce budworm defoliation on the potential for surface fires to torch (ignite the crowns of individual trees) and crown (spread between the crowns of multiple trees). Although we acknowledge that multiple factors affect surface fire intensity, we focus on simulating crown-fire occurrence for specified levels of defoliation and surface fire intensity. First, we used WFDS to simulate the interacting effects of defoliation and surface fire intensity on torching of a single tree and also to examine model sensitivity to (a) the distribution of defoliation within the canopy, (b) the drying of defoliated branches and (c) the spatial resolution of the model. Second, we used WFDS to simulate the interacting effects of defoliation and surface fire intensity on crowning in a row of trees.

Methods

We modelled a single tree for our torching simulations and replicated it for our crowning simulations, defining crown fuel for this tree with two components: foliage and small diameter branchwood (<5 mm; Brown and Reinhardt 1991; Call and Albini 1997; Scott and Reinhardt 2001; Keane *et al.* 2006; Reinhardt *et al.* 2006*a*; Mell *et al.* 2009). We based this modelled tree on a single mature, co-dominant, Douglas-fir tree that we measured in Colorado for another study. We selected this particular tree because it is a western spruce budworm host, could survive a high level of defoliation (Alfaro *et al.* 1982; Anderson *et al.* 1987; Brookes *et al.* 1987; Alfaro and Maclauchlan 1992; Powell 1994), is likely to torch due to low canopy base height (2 m) and is a validated species in WFDS (Mell *et al.* 2009). It was 12 m tall and 49 cm in diameter at breast height (1.3 m above the ground). WFDS determines the thermal and drag properties of fuel particles from surface area to volume ratio, fuel element (particle) density and fuel bulk density. For our single modelled tree, surface area to volume ratio and fuel element density were kept constant (Table 1) and we estimated crown fuel bulk density by dividing an estimate of the mass of crown fuels by an estimate of crown volume. We estimated the mass of each fuel component (foliage and small branchwood) by applying an allometric equation for interior Douglas-fir to the tree we measured in Colorado (Standish *et al.* 1985). We estimated crown volume by assuming the crown was a rectangular box. We made the crown rectangular to ensure consistent volumes among different cell sizes and fuel configurations. We estimated crown diameter (7 m) from an allometric equation (Bechtold 2004) and we measured the crown length of our tree in the field (tree height minus crown fuel base height, 10 m). We distributed crown fuel, i.e. branchwood and foliage, evenly throughout the crown volume (Table 2).

There are few quantitative estimates of defoliation by western spruce budworm; visual estimates range from 30 to 84% reduction in foliage (Alfaro *et al.* 1982; Powell 1994; Kolb *et al.* 1999; Bulaon and Sturdevant 2006). Based on this range, we simulated four levels of defoliation: none (0%), low (30%), moderate (50%) and high (80%) reductions in foliar mass, hence density.

To isolate changes to torching and crowning behaviour, we defined surface fires with a constant rate of spread and residence time over a specified range of surface fire intensities (Parsons *et al.* 2011; Contreras *et al.* 2012; Hoffman *et al.* 2012). Here surface fire intensity refers to Rothermel's (1972) reaction

Table 1. Parameters that define fuel particle properties in wildland–urban interface fire dynamic simulator (WFDS)

Fuel particle parameter	Branchwood	Foliage
Surface area to volume ratio (m^{-1})	1334	4000
Char fraction	0.25	0.25
Maximum burn rate ($kg\ s^{-2}\ m^{-3}$)	0.4	0.4
Maximum dehydration rate ($kg\ s^{-2}\ m^{-3}$)	0.4	0.4
Drag coefficient	0.375	0.375
Initial temperature (°C)	25[A]	20
Moisture content ratio	0.2–1	1
Particle density ($kg\ m^{-3}$)	520	520
Bulk density ($kg\ m^{-3}$)	0.2	0.0158–0.3153

[A]Branchwood was accidentally assigned a higher initial temperature than foliage, but this difference should be too small to materially affect ignition, which occurs at temperatures over an order of magnitude hotter than the initial temperature.

Table 2. Distribution of biomass within the crown

	Heterogeneous					
	Zone 1	Zone 2	Zone 3	Zone 4	Total	Homogeneous
Volume of the zone (m^3)	10	80	160	240	490	490
Undefoliated (0%)						
Foliar weight (kg)	3.153	25.228	50.456	75.683	154.520	154.520
Foliar bulk density ($kg\ m^{-3}$)	0.315	0.315	0.315	0.315		0.315
Low defoliation (30%)						
Foliar weight (kg)	3.153	25.228	50.456	29.327	108.164	108.164
Foliar bulk density ($kg\ m^{-3}$)	0.315	0.315	0.315	0.122		0.221
Moderate defoliation (50%)						
Foliar weight (kg)	3.153	25.228	48.879	0	77.260	77.260
Foliar bulk density ($kg\ m^{-3}$)	0.315	0.315	0.305	0		0.158
High defoliation (80%)						
Foliar weight (kg)	3.153	25.228	2.523	0	30.904	30.904
Foliar bulk density ($kg\ m^{-3}$)	0.315	0.315	0.016	0		0.063
All levels of defoliation (0–80%)						
Branch dry mass (kg)	1.997	15.977	31.954	47.931	97.860	97.860
Branch bulk density ($kg\ m^{-3}$)	0.200	0.200	0.200	0.200	0.200	0.200

intensity (kW m^{-2}), not Byram's (1959) fire line intensity (kW m^{-1}). We specified a spread rate of 0.138 m s^{-1} and a residence time of 13.8 s, with a 0.8-m s^{-1} wind.

We simulated a domain with a length and width of 48 m and a height of 24 m, and placed the tree in the centre of the domain. Proportional to the dimensions of the tree, this domain is similar to, or larger than those used for other single tree experiments with WFDS (Mell *et al.* 2009; Parsons *et al.* 2011).

Effect of defoliation on torching in a single tree

To model the effect of defoliation on torching fire behaviour we simulated multiple surface fires with a range of prescribed surface fire intensities (300–1250 kW m^{-2}) and iteratively burned a single tree with a range of defoliation levels (0–80%), 100% branch and foliar moisture content and a cell resolution of 1 m (Fig. 2*a*). To investigate the underlying physical drivers, we evaluated mass loss (dry weight and water weight; kg) and heat transfer rate (kW) over the course of individual simulations. The heat transfer rate (Q) is the net rate of heat transferred into a fuel element (by convection or radiation) summed across all fuel elements in a tree. Thus, a positive Q contributes to an increase in fuel element temperature. We also summarised each simulation in four ways: (1) foliage consumed during the simulation (percentage foliar loss by dry mass), (2) branchwood consumed

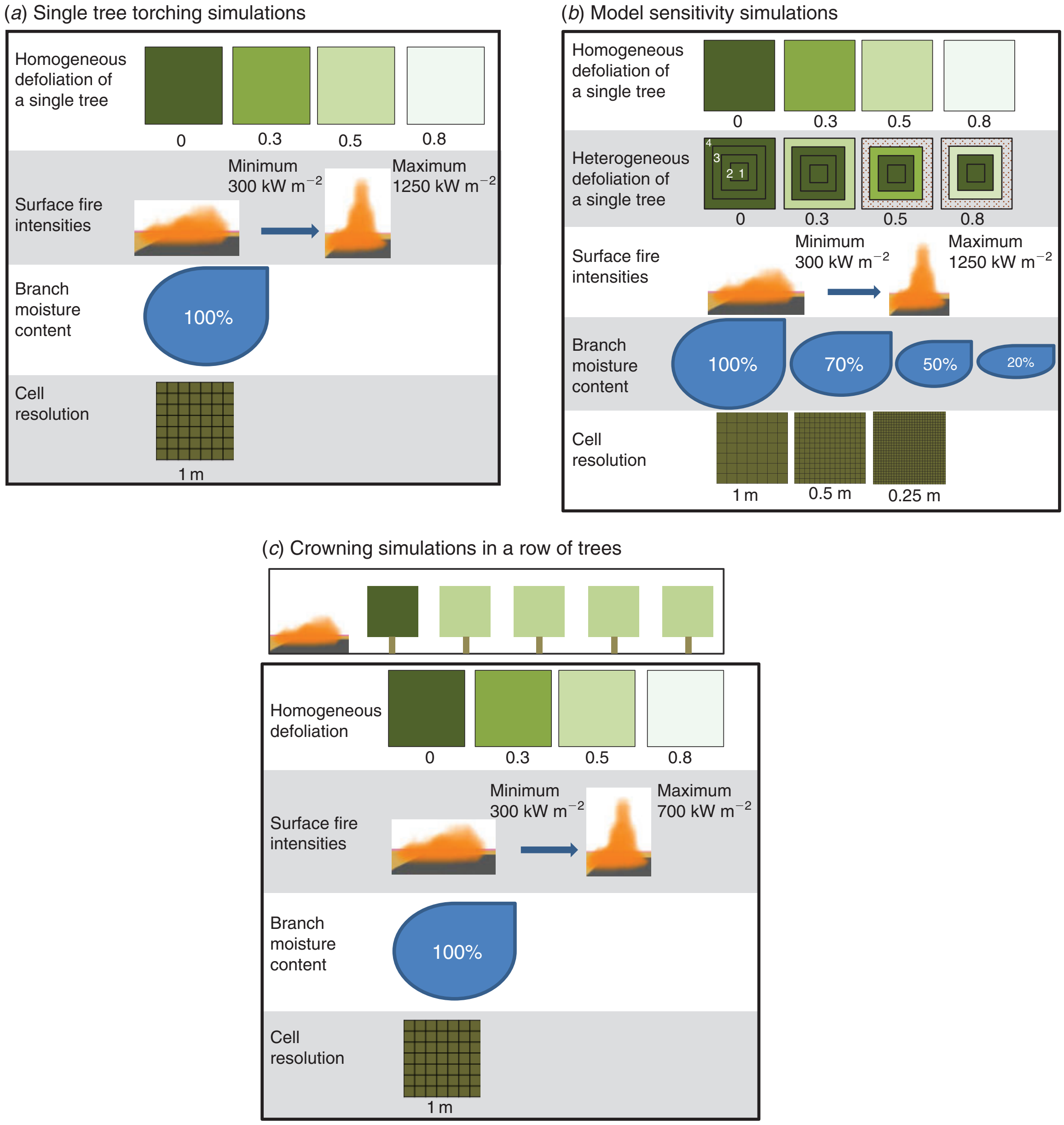

Fig. 2. Parameters of fire simulations: (*a*) parameters used to test torching of a single tree across multiple defoliation levels and surface fire intensities; (*b*) range of parameters tested for model sensitivity in comparison to simulations in (*a*). Parameters of simulations to test crowning within a row of trees (*c*). The fire first burns past one non-defoliated tree before reaching four defoliated trees. Foliar moisture was modelled at 100% for all simulations (*a*–*c*).

(percentage branchwood loss by dry mass), (3) cumulative net heat transfer (kJ) (Eqn 1),

$$H_{cumulative} = \sum_{t=0}^{t_{sim}} Q_{conv_t} \times dt + \sum_{t=0}^{t_{sim}} Q_{rad_t} \times dt \qquad (1)$$

computed as the sum over time of net heat transferred to the fuel elements by radiation and convection, and (4) torching threshold. Torching begins when a portion of the lower crown is exposed to a surface fire and combusts. In turn, heat from this combustion heats the fuel above and thus torches, i.e. propagates combustion upward through the crown. To distinguish between combustion of the base of the crown and upward propagation of combustion (i.e. torching), we used WFDS-predicted fuel consumption to define torching threshold as the minimum surface fire intensity at which 60% or more of the foliage is consumed. For example, we consider a tree that is 80% defoliated to torch when 60% of its remaining foliage has been consumed.

Model sensitivity to distribution of defoliation within the crown

We compared a simple homogeneous tree to a more realistic heterogeneous tree to see whether the effects of defoliation on torching were sensitive to the distribution of defoliation within the canopy, across a range of surface fire intensities (Fig. 2*b*). To simulate heterogeneous defoliation, we divided the canopy into 4 concentric rectangular zones, each 1 m in width and extending the entire length of the 10-m crown (Fig. 2*b*). At each defoliation level, foliage was removed from the outermost zone (zone 4) until it contained no foliage, then foliage was removed from the next zone inward (zone 3), and so on until the defoliation level was met (Table 2). This separated the tree into an outer defoliated zone, where only branchwood remained, and an inner un-defoliated zone with unchanged fuel load and bulk density (Fig. 2*b*).

Model sensitivity to drying of defoliated branches

We tested four levels of branchwood moisture content in homogeneously defoliated trees to assess the potential effects of drying of defoliated limbs: 20, 50, 70 and 100%. A realistic defoliated tree has portions of branchwood with and without needles. We calculated the branchwood moisture content of the entire canopy as a weighted average of the moisture content of the defoliated and un-defoliated branchwood. We maintained foliar moisture at 100% for all simulations.

Model sensitivity to spatial resolution

CFD models, such as WFDS, are sensitive to the resolution used in calculations; smaller cell sizes resolve gradients better and can result in more accurate calculations (Mell *et al.* 2009; Parsons *et al.* 2011). Here, we tested the effects of defoliation at three levels of cell resolution (cubes of 1, 0.5, and 0.25 m on a side).

Effect of defoliation on fire propagation between trees (crowning)

To model the effect of defoliation on crowning, we created a row of five identical trees with 1-m spacing by replicating the single modelled Douglas-fir tree we used in the torching simulations. To ensure that torching occurred and therefore that crowning would be possible, we did not defoliate the first tree in the row. We defoliated the remaining four trees to the same level in a given simulation: none (0%), low (30%), moderate (50%) or high (80%; Fig. 2*c*). We simulated a range of surface fire intensities (300–700 kW m^{-2}), based on the torching behaviour we observed in the single-tree simulations. Crowning depends on wind speed and crown spacing (Rothermel 1991; Scott and Reinhardt 2001). We used a wind speed (6 m s^{-1}) in which fire spread between tree crowns is common (Cruz and Alexander 2010), and was sufficient to spread fire between tree canopies separated by 1 m (Contreras *et al.* 2012). We measured the effect of defoliation as the cumulative net heat transferred by radiation and convection from the canopies of all four defoliated trees combined.

Results

Effect of defoliation on torching in a single tree

Simulated defoliation by western spruce budworm inhibited the vertical propagation of fire into tree crowns. Increasing defoliation resulted in lower cumulative net heat transfer across all surface fire intensities (Fig. 3*d*), higher torching thresholds (surface heat release resulting in 60% foliage consumption; Fig. 3*a*), and lower peak heat transfer rates (Fig. 4*a*, *b*). For example, at a surface fire intensity of 1000 kW m^{-2}, a moderately (50%) defoliated tree transferred 60% of the heat transferred from un-defoliated trees (Fig. 3*d*). In turn, the torching threshold increased from 475 kW m^{-2} for an un-defoliated tree to 625 kW m^{-2} at 50% defoliation (Fig. 3*a*). As the surface fire passed beneath un-defoliated trees, combusting fuel transferred heat at high rates, igniting the fuel above (Fig. 4*a*). With increasing defoliation, combusting material transferred low amounts of heat evenly over the simulation duration (Fig. 4*b*). This lower intensity heat resulted in low cumulative net heat transfer.

More defoliation resulted in less canopy consumption by fire, regardless of surface fire intensity (homogeneous case, Fig. 3*b*). For example, at a surface fire intensity of 700 kW m^{-2}, 2 kg (1%) of the foliage of an un-defoliated tree was not consumed, compared with 15 kg (19%) of foliage not consumed on a moderately (50%) defoliated tree.

Model sensitivity to distribution of defoliation within the crown

The distribution of defoliation within the canopy had little effect on the cumulative net heat transfer (Fig. 3*d*), but changed the maximum heat transfer rate and duration of heat transfer (Fig. 4*b* *v.* 4*c*). The average difference in net heat transfer between heterogeneous and homogeneous distributions was 32 184 kJ or 19% of the heat transferred by a homogeneous tree (Fig. 3*d*). Even the maximum difference (168% of a homogeneous tree; 50% defoliation; 475 kW m^{-2} surface fire intensity) was much smaller than the difference in heat transfer that resulted from defoliation alone at this surface fire intensity (500 kW m^{-2}); an un-defoliated tree released 665 500 kJ (464%) of a moderately (50%) defoliated homogeneous tree. However, homogeneously defoliated trees consistently transferred heat at low rates during the entire simulation (Fig. 4*b*), whereas heterogeneously

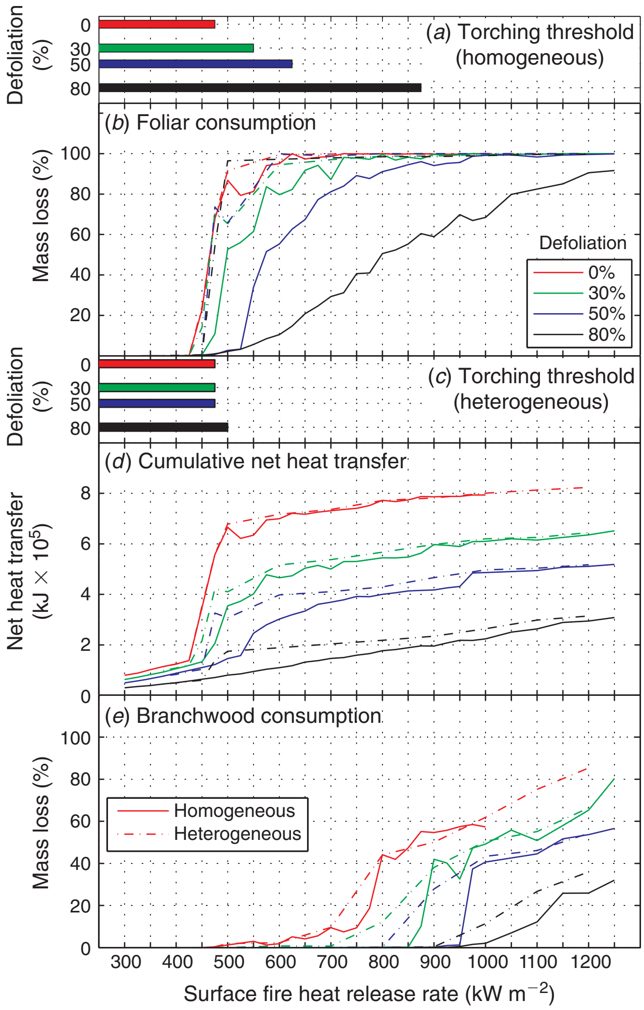

Fig. 3. Simulated effects of defoliation by western spruce budworm across a range of surface fire intensities on torching behaviour in a single Douglas-fir tree. Summarised by (*a*) torching threshold of homogeneously defoliated trees, (*b*) foliar consumption (percentage of dry mass), (*c*) torching threshold of heterogeneously defoliated trees, (*d*) cumulative net heat transferred to foliage and small branchwood by radiation and convection (kJ), (*e*) branchwood consumption (% of dry mass). Note that mass loss in part (*b*) refers to the percentage consumption of the foliage remaining after defoliation. Parameters for the simulations are given in Fig. 2*a*–*b*.

defoliated trees transferred heat at a high rate over short periods of time (Fig. 4*c*).

In contrast to homogeneous defoliation, torching thresholds in the heterogeneous cases did not vary, regardless of defoliation level (Fig. 3*c*). This indicates that in homogeneously defoliated trees combustion only occurs where the tree is exposed to an adequately intense surface fire, in contrast, in heterogeneously defoliated trees, combustion is propagated upward. This is apparent in their different patterns of net heat transfer rates (Fig. 4*b* *v.* 4*c*). The heterogeneously defoliated tree has high intensity net heat transfer (convective max of 6339 kW) which can ignite other crown material during a small period where combustion is occurring (Fig. 4*c*). The homogeneously defoliated tree has low intensity net heat transfer, although over a longer period of time (Fig. 4*b*).

Model sensitivity to drying of defoliated branches

Reducing branchwood moisture below 100% reduced the torching threshold of highly defoliated trees but not for a low or moderately defoliated tree (Fig. 5). Branchwood was not noticeably consumed, at surface fire intensities less than 650 kW m^{-2} (Fig. 3*e*), even at low (20%) moisture content. The torching threshold is below this surface fire intensity for all but high (80%) levels of defoliation, indicating that foliage ignites at lower surface fire intensities than branchwood (Fig. 4*d*), and thus branchwood moisture does not affect torching unless foliar mass is reduced to the point where it requires a higher surface fire intensity to ignite than is required by branchwood.

Branchwood drying did cause a small increase in cumulative net heat transfer (Fig. 5*c*–*d*). However, this increase was never greater than the reduction in cumulative net heat transfer due to defoliation.

Model sensitivity to spatial resolution

Spatial resolution (i.e. cell size) had little effect on cumulative net heat transfer or on the torching threshold, regardless of the level of defoliation or surface fire intensity (Fig. 6). On average, foliar consumption only differed by 10% and cumulative heat transfer differed by 23%. The effect of model resolution did not bias the results consistently towards higher or lower heat transfer. The difference in heat transfer among cell resolutions only exceeded those caused by defoliation at low surface fire intensities near torching thresholds (e.g. surface fire intensity of 450 kW m^{-2}).

Effect of defoliation on fire propagation between trees (crowning)

Simulated defoliation by western spruce budworm inhibited the horizontal propagation of fire between tree crowns. Regardless of surface fire intensity, defoliation reduced the net heat transferred by crowning trees (Fig. 7), which in turn reduced the horizontal propagation of fire, i.e. crowning behaviour. For trees downwind of the un-defoliated ignition tree, net heat transfer decreased as defoliation increased for both heterogeneous and homogeneous trees. For example, at a surface fire intensity of 300 kW m^{-2}, an un-defoliated row of trees transferred 3.5 times the heat transferred by a highly defoliated row (590 040 kJ *v.* 167 310 kJ).

Discussion

Effect of western spruce budworm on fire

In our simulations we found that defoliation consistently reduced cumulative net heat transfer across a range of surface fire intensities. Vertical propagation of fire diminished in individual trees with reduced fuel density, whereas the horizontal propagation of fire between trees was reduced with increasing defoliation regardless of whether the defoliation reduced single tree fuel density and load (homogeneous) or reduced single tree fuel load without changing fuel density (heterogeneous). Single, homogenous, highly defoliated trees experienced less torching, and moderately defoliated trees (50%) required approximately twice the surface fire intensity of un-defoliated trees to produce the same heat transfer (>27 000 kJ; Fig. 3). This damping effect on torching is likely to affect crown fire spread at the stand scale.

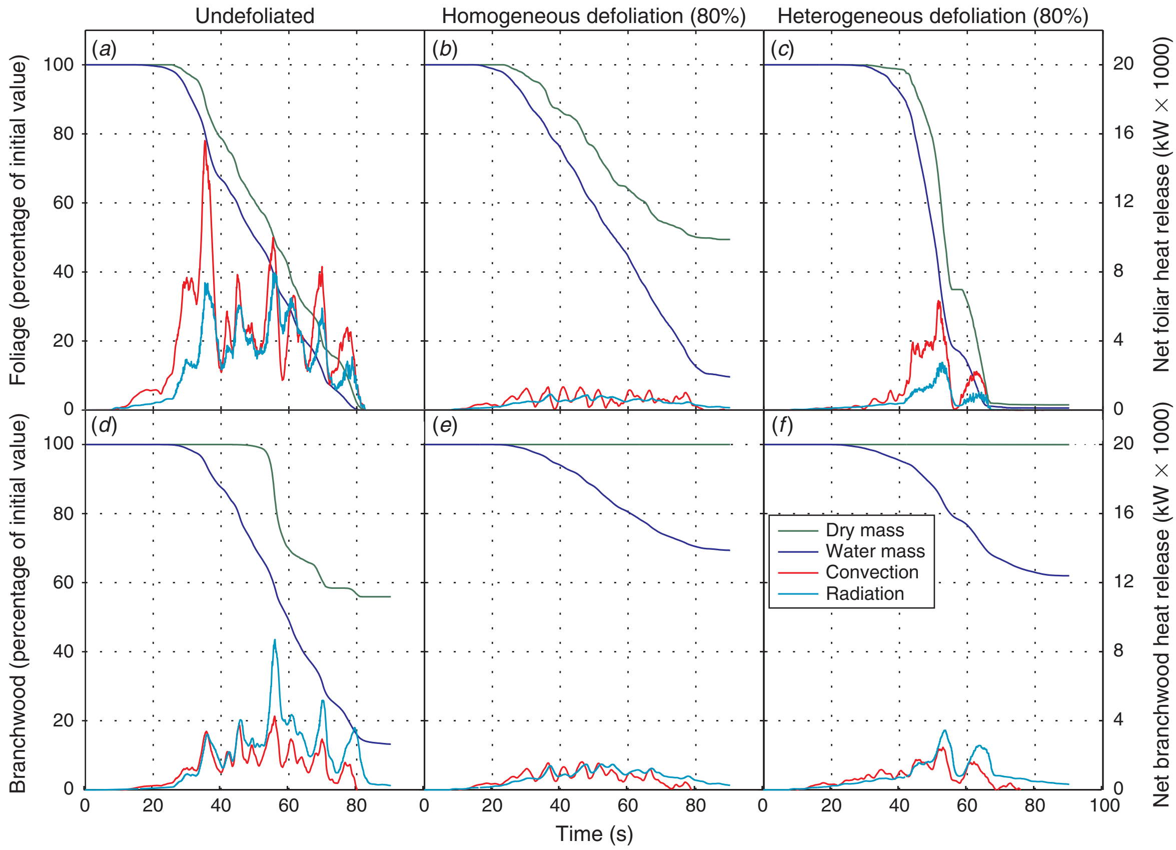

Fig. 4. Mass loss and instantaneous heat transfer rate for foliage and small branchwood (<5 mm) over the course of individual simulations with a surface fire intensity of 800 kW m^{-2}, 100% branchwood moisture, 1-m cell resolution for an un-defoliated tree (*a*, *d*), a tree with 80% homogeneously distributed defoliation (*b*, *e*), and a tree with 80% heterogeneously distributed defoliation (*c*, *f*). Red and turquoise lines correspond to the right *y*-axis and indicate instantaneous measurements of convective (red) and radiative (turquoise) heat transfer rate (kW). Blue and green lines correspond to the left *y*-axis and indicate water (blue) and dry (green) mass of the fuel component as a percentage.

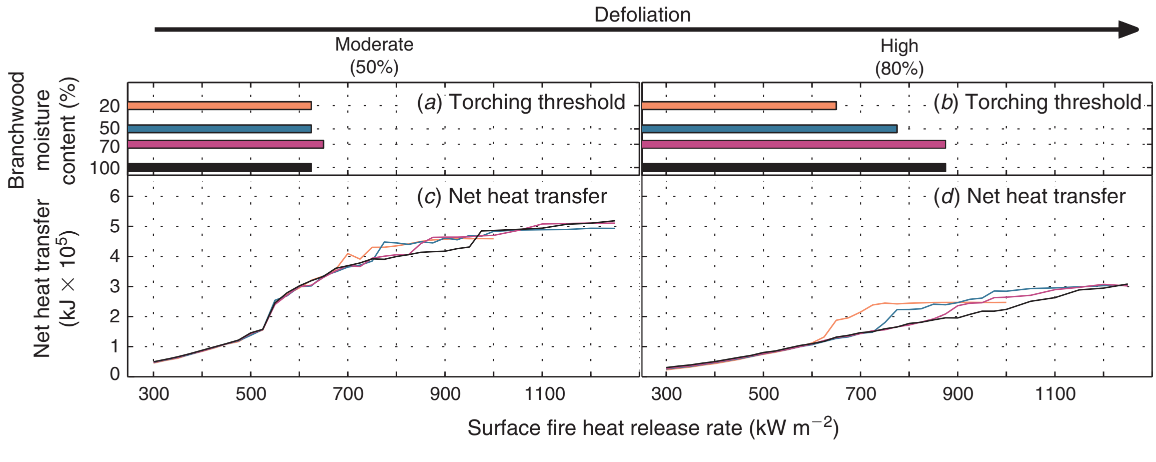

Fig. 5. Model sensitivity to the moisture content of defoliated branches, measured as the cumulative net heat transferred by radiation and convection to foliage and small branchwood (<5 mm) (*c*–*d*) and torching threshold (*a*–*b*) in a homogeneously defoliated tree with 1-m resolution. Colours of bars in (*a*) and (*b*) correspond to moisture contents of lines in (*c*) and (*d*): black, 100%; pink, 70%; teal, 50%; orange, 20%.

In real stands, western spruce budworm likely modifies fire behaviour in myriad ways. Reduced foliage in the canopy may lead to reduced wind drag, reduced shading and altered understorey plant composition, fuel moistures and wind fields. Here we isolated the effects of western spruce budworm on a single tree and tested them across a range of surface fires that could arise from any number of fuel and weather scenarios. This approach leaves many questions for future research about

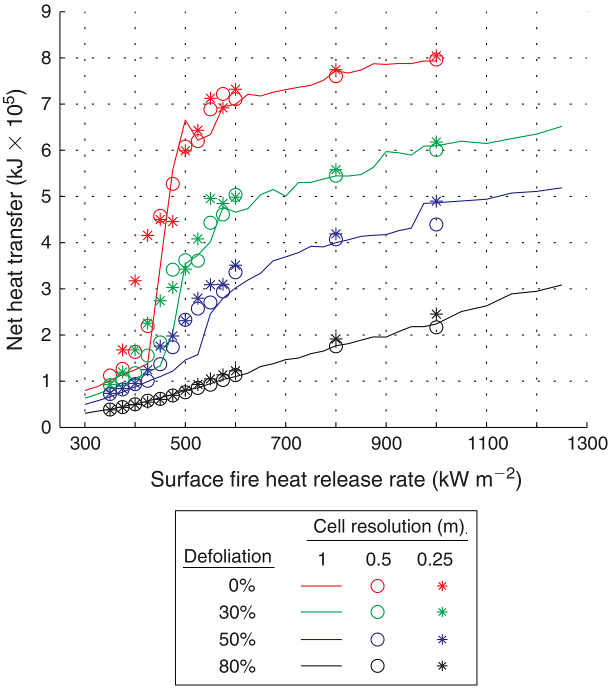

Fig. 6. Model sensitivity to the resolution simulated, measured as the cumulative net heat transferred by convection and radiation to foliage and small branchwood (<5 mm). Colours correspond to defoliation level: red, 0%; green, 30%; blue, 50%; black, 80%.

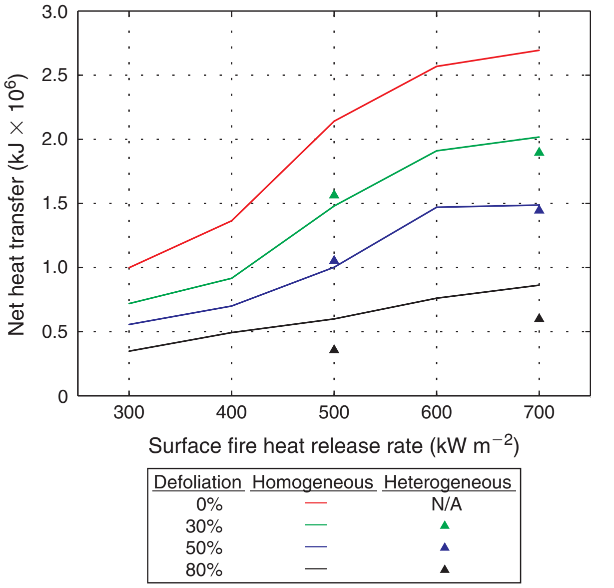

Fig. 7. Simulated effects of defoliation by western spruce budworm and surface fire intensity on crowning fire behaviour in a row of Douglas-fir trees. Values displayed are the cumulative net heat transferred by radiation and convection to foliage and branchwood in the four defoliated trees. Parameters for the simulations are given in Fig. 2*c*.

changes in surface fuels and winds in realistic stands, but allowed us to understand potential changes in torching and crowning resulting from western spruce budworm that could potentially be applied to a wide variety of stands.

Potential effects of reduced crown fire behaviour

One potential implication of our work is that areas significantly defoliated by western spruce budworm could act as a deterrent to crown fire spread. Infested stands may inhibit crown fire initiation or spread for years after an outbreak, until foliage is fully recovered. Relatively low mortality of large trees from western spruce budworm in conjunction with long outbreak durations create persistent stands of defoliated overstorey trees. Combined with high mortality of intermediate and sapling host trees and reduced cone production (Fellin and Dewey 1982; Bulaon and Sturdevant 2006), closed stands may persist with little regeneration even several years after outbreaks have ended. This may create stands with few ladder fuels, further reducing a stand's susceptibility to stand replacing fires. The reduced crown fire behaviour found in our simulations suggest that western spruce budworm may create a stand structure more conducive to non-lethal surface fire with limited torching of isolated trees instead of stand replacing fire.

Western spruce budworm may also help maintain fire regimes with frequent surface fire. Both fire and western spruce budworm outbreaks reduce competition among surviving trees for light and nutrients, while killing shade-tolerant understorey trees. This promotes the survival of fire-resistant, shade-intolerant species such as ponderosa pine. In the south-west, outbreaks of the western spruce budworm and wildfires appear to have alternated as the dominant disturbance type over the last several centuries, with defoliation more common during wetter intervals and fire predominant during dry intervals (Swetnam and Betancourt 1998). We suggest that defoliation by the western spruce budworm may have helped mature Douglas-fir and true fir trees survive subsequent fires by reducing ladder fuels and the probability of torching, whereas fires might have helped reduce the severity of subsequent outbreaks by reducing the density and vertical continuity of host trees, similar to the 'natural thinning' function proposed for the eastern spruce budworm (Sturtevant *et al.* 2012).

Our modelling approach

The detailed modelling approach employed here facilitates a more in-depth examination of western spruce budworm defoliation effects on fire behaviour than previous work, but our methods have some limitations. We used a very simple representation of a single tree or group of 4 trees, with rectangular tree crowns, and focussed on the key effects of defoliation and branch moisture on fire behaviour in canopies, to ensure that our work could be easily replicated and to create clear links between canopy fuel changes and torching and crowning fire behaviour.

There are several potential aspects of budworm defoliation that we did not test. Our simulations examining fire spread between adjacent tree crowns were limited to a small set of identical trees. Real stands, of course, are more diverse, with both host and non-host trees, and with trees of different heights. Small understorey host trees, often killed by western spruce budworm (Alfaro *et al.* 1982; Alfaro and Maclauchlan 1992; Powell 1994), could potentially increase torching potential by acting as ladder fuels, particularly if they died before all foliage was consumed, leaving dry needles. We did not model this aspect as there is little data quantifying how much fuel is left, or how long it persists, in these trees. Similarly, we did not model top kill, a common effect of western spruce budworm (Alfaro and Maclauchlan 1992; Powell 1994). Although we assume that top kill does not directly affect torching because torching is initiated at the crown base, top kill reduces total canopy fuel, which could decrease crowning. Top kill also affects the vertical distribution of defoliation, which could change the level of defoliation necessary to alter torching, behaving more like the heterogeneous defoliation case. Also, detached red needles have been observed hanging in budworm hibernacula (Fellin and Dewey 1982; Brookes *et al.* 1987). However, the mass, moisture content and duration of this needle drape is unknown. We did not address any changes in surface fuels or surface level winds that may alter surface fires, instead using a range of surface fire intensities intended to represent surface fires that could result from a wide array of surface fuel or weather scenarios.

Our use of fixed spread rate surface fires facilitated a straightforward assessment of changes in torching by isolating the effects of canopy fuel changes. However, this approach does not fully represent the interaction between surface fire and crown fire, which can be complex. In a more realistic scenario, the increased wind used to facilitate crown fire in the multi tree scenarios would have altered the surface fire. Surface fires initiate crown fires, crown fires increase the overall fire intensity and contribute to increased surface fuel heating, and spotting ahead of the fire (Van Wagner 1993; Scott and Reinhardt 2001). This interaction varies with wind, fuel moisture, fuel type and fuel structure.

We eliminated between-tree variability in fuel quantity and associated fire behaviour by focusing our simulations on a single tree, representing the tree crown as a simple, rectangular volume. Although it is common to use a rectangular volume when considering canopy bulk density for uniform stands (Keane *et al.* 1998) this shape is not very accurate for individual tree crowns; it increases the crown volume (relative to cone or cylinder shaped crowns) and consequently decreases crown bulk density. This simplified geometry was intended to ensure consistent volumes between different cell sizes and fuel configurations. However, the crown bulk densities we used are well within the range observed for Douglas-fir trees, and should be applicable to other trees with similar crown bulk densities and crown base heights.

Implications for operational fire behaviour modelling

Our study looked at relative changes in torching threshold due to defoliation. We found that the ability for fuel at the base of the tree to ignite the fuel above (i.e. torch) changes with crown bulk density when foliar moisture and canopy base height are held constant. However, we found that torching initiation was not affected when foliage load (i.e. mass) is reduced, but bulk density of the remaining crown is not reduced (as in the heterogeneous experiments). Operational fire behaviour models in the US identify transitions from surface to crown fire using only canopy base height and canopy fuel moisture (Finney 1998; Scott and Reinhardt 2001; Reinhardt and Crookston 2003; Andrews 2009), assuming that flame contact with the base of the tree is the critical factor in torching initiation. Other models, however, include bulk density in predicting torching characteristics (Cruz *et al.* 2005, 2006) suggesting that flame contact with crown fuel does not necessarily initiate torching. These studies identify 0.01 to 0.05 $kg\,m^{-3}$ as the minimum stand level canopy bulk density for torching, similar to the tree-level crown bulk density of our high defoliation case (0.063 $kg\,m^{-3}$). This agreement is encouraging, but it suggests, as others have (Cruz and Alexander 2010; Alexander and Cruz 2013), that more work is needed to understand torching initiation.

Small branchwood, even at low moisture content, did not have a large effect on crowning in our simulations. Small branchwood is included by many fuel calculation models (Scott and Reinhardt 2001; Reinhardt and Crookston 2003; Keane *et al.* 2006; Reinhardt *et al.* 2006*a*) because it is thought that it is available to the flaming front of an advancing crown fire. Several modelling and empirical studies indicate that a portion of small branchwood is consumed in a crown fire (Brown and Reinhardt 1991; Call and Albini 1997; Mell *et al.* 2009). In our simulations small branchwood ignites at higher surface fire intensities than foliage, even when concurrent foliage is burning (Fig. 4*d*). Heat absorption depends on both surface area to volume ratio and packing ratio (bulk density/particle density). Branchwood has both a lower surface area to volume ratio than foliage and a lower packing ratio in all but the high (80%) defoliation case, which makes it absorb heat more slowly. This explains why it requires higher heat transfer rates to reach ignition. Slow heat absorption could support the idea that branchwood may be consumed during smouldering combustion after the flaming front has passed (Call and Albini 1997; Reinhardt *et al.* 2006*b*; Mell *et al.* 2009). In our simulations, we used the midpoint of the branchwood size class (2.5 mm) to calculate the surface area and volume (cf.,Mell *et al.* 2009) and used the surface area to volume ratio for Douglas-fir foliage presented in the same paper. The midpoint may not accurately represent the distribution of branch weight within the size class, underestimating the surface area to volume ratio. The effect of branchwood fuel load in operational crown fire models is complex, and based on our simulations, we suggest that further research is warranted.

We investigated within-tree fuel heterogeneity and found that it affected vertical fire propagation, but not total heat transfer. Loss of canopy fuel did not alter the torching threshold if canopy bulk density was kept constant, but heat transfer was decreased from the reduced foliage load (i.e. mass) regardless of the distribution of that fuel within the canopy. Heterogeneity affects fire behaviour both within (Mell *et al.* 2009; Parsons *et al.* 2011) and among trees (Linn *et al.* 2005; Parsons *et al.* 2010; Contreras *et al.* 2012; Hoffman *et al.* 2012). This raises questions about the scale at which heterogeneity is important. Canopy fuels are highly heterogeneous at the tree scale, with substantial differences not only in spatial distribution, but also size class, surface area to volume ratio, and chemical composition. At the stand scale, variation in tree size, species and crown distance add further heterogeneity. More research is needed to better understand the effects of fuel heterogeneity on fire behaviour.

The effect of defoliation by the western spruce budworm may be applicable to other defoliators. For instance, our homogeneous, high-defoliation simulations could be representative of patterns of defoliation from the Douglas-fir tussock moth (*Orgyia pseudotsugata* McDunnough). Like the western spruce budworm, this species feeds on Douglas-fir and true firs in western North America (Wickman *et al.* 1981). However, its outbreaks are brief and defoliation rates severe in both new and old foliage (Wickman *et al.* 1981). We suggest that defoliation by the Douglas-fir tussock moth may reduce torching and dampen the spread of crown fire from un-defoliated trees into clumps of defoliated trees, similar to our simulated effects of western spruce budworm.

Future needs

This study focussed on the fine scale effects of western spruce budworm on fire. Our results are consistent with the findings of other studies of the historical impacts of western spruce budworm on fire that have been observed over large areas and long time periods, but much remains unknown. For example, stand-scale distributions of attack, changes to surface fuels, surface moisture regimes and wind fields are all unknown. Among the factors we investigated, changes in crown biomass were the most important effect of western spruce budworm on canopy fire, but the interaction with potential surface fire changes remains unknown. To answer these larger questions, more must be known about changes induced by the western spruce budworm in forest type and canopy and surface fuels.

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