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Assessing the exposure of the built environment to potential ignition sources generated from vegetative fuel

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Abstract. We assessed the exposure of the built environment to potential ignition sources generated from vegetative fuel for four communities in the province of Alberta, Canada. Ignition processes generated by burning vegetation that were included in the analysis were radiant heat, short-range spotting, and longer-range spotting. Results were used to map the boundaries of the wildland–urban interface and to delineate zones within each community that identify the degree to which these areas represent potential wildfire entry-points into the wildland–urban interface. The assessment method can be used to set priorities for mitigation activities; compare conditions within and between communities and over time; and identify priority areas for time- and resource-intensive site assessments that are often completed for individual structures located in the wildland–urban interface. We compared results among the four case-study communities and demonstrated an application of the approach for evaluating community fuel treatment plans. Factors that influenced the exposure of the built environment to potential ignition sources differed among the communities, which suggested the need for community-specific mitigation strategies. Spatial patterns of areas with elevated ignition exposure reflected not only the amount of ignition-producing vegetation around the built environment, but also the size and arrangement of fuel patches in relation to the unique morphology of the community and the occurrence of occluded interface zones.

Additional keywords: community, defensible space, fire behaviour, fire management, FireSmart, FireWise, wildland–urban interface.

Introduction

When a wildfire encounters developed land, there can be significant negative impacts on buildings, infrastructure, and the concentrations of people and socioeconomic activities that occur in these areas. Identification of areas where wildland fires can spread into the built environment is critically important for setting priorities for prevention, preparedness, and mitigation activities aimed at minimising negative fire impacts. The 'built environment' generally refers to surroundings constructed by people and used to stage human activities. We use the term to describe areas with human-made buildings and structures, as opposed to natural features. The 'wildland–urban interface' (WUI) is a term commonly used to describe areas where wildfires and the built environment have the potential to interact (Butler 1974). This can occur where the boundaries of the built environment abut wildland vegetation (i.e. the classic interface); where the built environment is intermixed with wildland vegetation (i.e. the mixed interface); and where islands of vegetation occur within the built environment (i.e. the occluded interface) (Laughlin and Page 1987; Davis 1988).

Whereas specific criteria related to population and housing density can help to define the interface (USDA and Department of the Interior 2001), the built environment can only be considered part of the WUI if it consists of combustible manufactured fuels that are located within the range of ignitions generated from nearby combustible vegetation (Butler 1974). Ignition within the built environment can occur from several processes: convection, where a structure ignites as a result of convective heat transfer from direct contact with flames; radiation, where a structure ignites as a result of radiant heat emanating from a flaming fire front; and firebrands, where a structure ignites as a result of contact with descending burning embers that have been propelled aloft and ahead of the fire front in response to convective and wind activity (i.e. short- and longer-range spotting). The boundaries of the interface will depend on the specific characteristics of nearby combustible vegetation, that is, the ability of that vegetation to generate ignitions over a distance. This distance can be expected to vary as a function of vegetation type, season, characteristics of surrounding landscape features such as slope, and weather conditions at the time of the fire, which will influence fire behaviour, convective activity, and airborne firebrand transport.

Whereas the exact distance covered by ignition processes will depend on site-specific conditions at the time of a fire, simplifications about these conditions are used to produce strategic-level assessments applicable to larger spatial scales and longer time periods. Wildland–urban interface maps developed for national or regional areas typically combine population or housing data with satellite-based land type classifications (Stewart *et al.* 2009) and sometimes use knowledge of fire behaviour processes to incorporate ignition processes. Radeloff *et al.* (2005) identified WUI areas based on a maximum distance (2.4 km) from a heavily vegetated area with a minimum size of 5 km^2. This distance threshold was intended to reflect the limit of potential exposure to airborne firebrands from forest fires. The resulting strategic-level wildland–urban interface map can help to define the general

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extent of interface areas, but is far too coarse to inform local mitigation activities, such as fuel treatment planning. It is possible to apply similar methods for investigating ignition processes at the community scale. In an assessment of the ecological connectivity of habitat in urban areas, Bierwagen (2005) rated the potential for wildfires to move between habitat patches using a maximum firebrand travel distance of 500 m. Despite the urban setting, the analysis still involved a relatively coarse scale of analysis (30- to 100-m grid cells) and did not distinguish among different fuel types or different ignition processes.

In contrast, site-specific assessments of the receptivity of built structures to ignition from wildfires require detailed inputs describing both the built structure and the fire behaviour involved. For example, predictive statistical models have been developed from post-fire data to calculate the probability of a house surviving a fire as a function of variables such as fire intensity, building materials, proximity to flammable vegetation, and attendance by householders (Wilson and Ferguson 1986). The Structure Ignition Assessment Model (SIAM) was designed to rate the potential for structure ignitions from inputs that include roof flammability, exterior materials, topography, wind speed, temperature, fire behaviour, and the type, area, proximity, and moisture content of natural and manufactured flammable materials (Cohen 1995). The data-intensive nature of these structure ignition models makes them impractical for widespread application.

The FireWise program in the United States and the FireSmart manual in Canada (Partners in Protection 1999, 2003) have been used to promote simplified site-level rating systems that encompass some of the key interactions identified in structure ignition models, yet are suitable for use by homeowners and fire management practitioners. Reference to a critical distance associated with ignition processes is a prominent component in all rating systems, which typically call for the clearing or modification of flammable vegetation within 30 m or more around a structure. This buffer between structures and surrounding flammable vegetation, sometimes referred to as 'defensible space' or a 'fuel-modified area' is based on case-study analysis and severe-case assumptions about flame radiation and exposure time (Cohen 2000).

Site-level assessments are typically concerned with ignition processes in the immediate vicinity of the structure, and therefore focus on the potential for ignitions from radiant heat and convection that occur over relatively short distances. Ignition from short- and longer-range spotting may be considered indirectly by rating the receptivity of structures to firebrand ignitions (i.e. roofing material). Because exposure to ignitions generated from vegetation beyond the immediate vicinity of a structure is not considered explicitly, site-level assessments alone are not well suited for determining whether or not a given area of the built environment is located within the wildland–urban interface. Site-level assessments also typically ignore the amount or degree of exposure to ignition-generating fuels. For example, FireSmart (Partners in Protection 2003) assessments rate the presence or absence of different forest vegetation types within 30 m of a structure, but not the quantity of that vegetation.

The extent of surrounding areas relevant to a comprehensive assessment of ignition exposure in the built environment will depend on the fire behaviour processes and vegetation types under consideration. For example, exposure to firebrand ignition sources will depend on the distances associated with the transport of airborne firebrands generated from a given fuel type. These distances can be defined from models of maximum spot-fire distances developed for some fuel types (e.g. Albini 1979, 1981, 1983), analysis of case studies, or observations of common wildfire spotting distances. When combined with fine-scale vegetation maps surrounding the built environment, critical distances associated with ignition processes provide a means of assessing the wildland–urban interface at the community or neighbourhood scale.

We used the degree or level of exposure of the built environment to potential ignition sources generated from vegetative fuel as the basis for assessing the extent of the wildland–urban interface across four communities in the province of Alberta, Canada. By integrating information about fire behaviour processes with buffer mapping in a geographical information system, the approach includes aspects of existing site-level and national and regional-level approaches. Our objective was to develop a standardised assessment method that avoided data-, time-, and resource-intensive procedures that would render the process prohibitively complex or detailed for routine applied use by fire management practitioners, but that was also detailed enough to inform specific fire management activities around communities, such as fuel treatment planning. In this paper, we investigate ignition exposure differences within and between the four communities and demonstrate an application of the approach for evaluating community fuel treatment plans.

Methods

Study area

We conducted wildland–urban interface assessments for four communities in Alberta, Canada (Fig. 1): Fox Creek (54°24′N, 116°48′W), population 2337, 1.7 km^2 in size; Slave Lake (55°17′N, 114°46′W), population 6600, 5.5 km^2 in size; Swan Hills (54°43′N, 115°24′W), population 1807, 1.5 km^2 in size; and Whitecourt (54°09′N, 115°41′W), population 8747, 8 km^2 in size. Three of the communities (Slave Lake, Fox Creek, and Whitecourt) are located in the Central Mixedwood Subregion of the Boreal Natural Region. The dominant tree species in this area is aspen (*Populus tremuloides* Michx.), intermixed with white spruce (*Picea glauca* (Moench) Voss) forests on uplands (Downing and Pettapiece 2006). In contrast, Swan Hills is located in the Upper Foothills Subregion of the Foothills Natural Region, which is dominated by closed-canopy conifer stands of even-aged lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.), and black (*Picea mariana* (Mill.) B.S.P.) and white spruce (*Picea glauca* (Moench) Voss) (Downing and Pettapiece 2006).

Fire is a dominant and natural disturbance in the landscape surrounding the four communities. In this region, forest fires are supported primarily by conifer fuels, such as lodgepole pine, white spruce, and black spruce, whereas deciduous fuels, such as aspen, limit or arrest fire ignition and spread (Cumming 2001; Krawchuk *et al.* 2006). The natural fire regime includes frequent small lightning-ignited fires and relatively infrequent stand-replacing crown fires that burn vast areas (Tymstra *et al.* 2005). All four communities fall within a single fire-weather

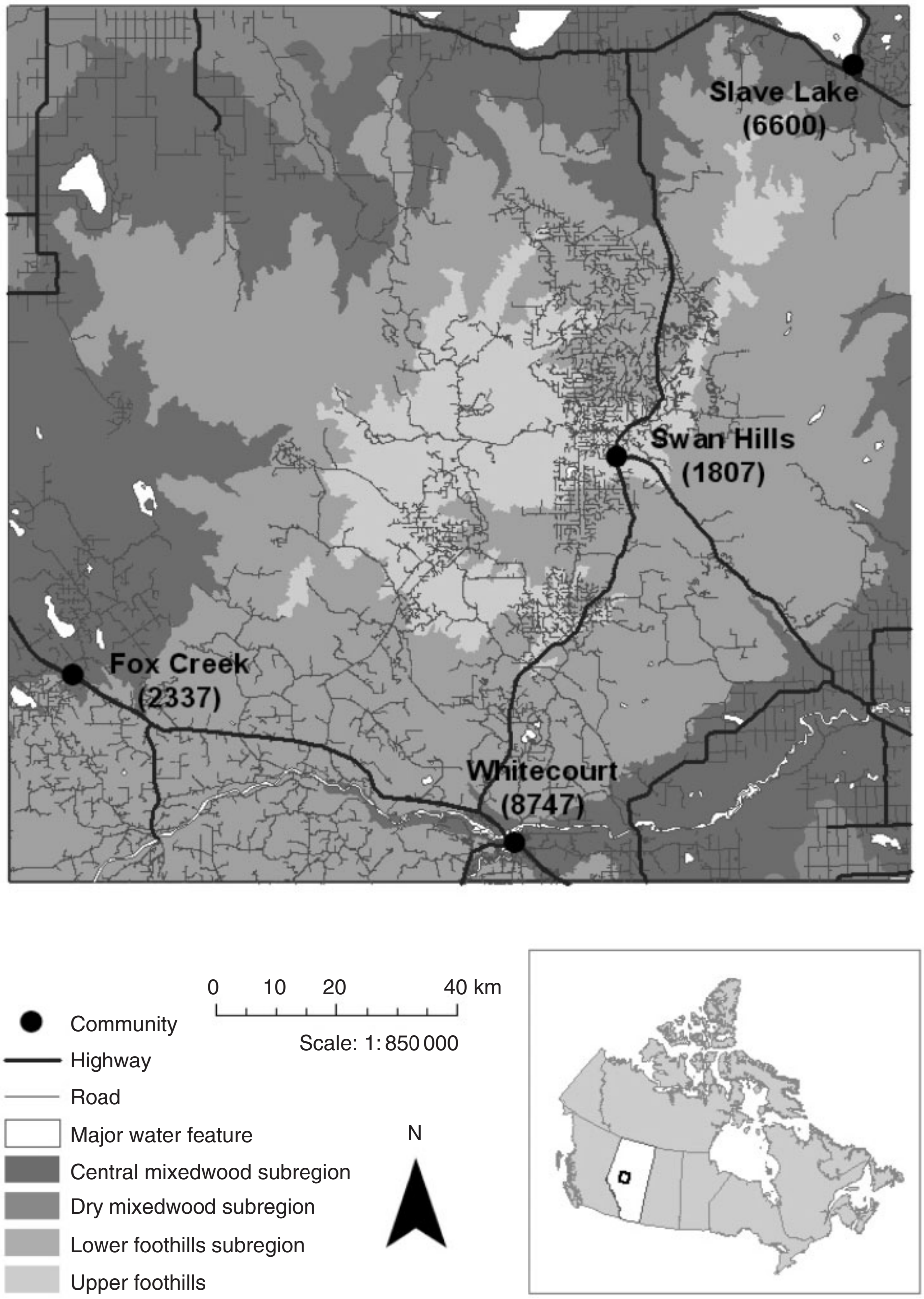

Fig. 1. Location of the four case-study communities in the province of Alberta, Canada. Population is shown in parentheses. Subregions refer to the provincial ecological land classification system (Downing and Pettapiece 2006).

regime (Beverly *et al*. 2009, fig. 5*d*). Records of fires that occurred between 1976 and 2003, obtained from the agency responsible for forest fire management in the province, Alberta Sustainable Resource Development, indicate that densities of fires within a 10-km buffer zone surrounding each community have been relatively consistent among the four communities. Fire densities were 0.4 km^{-2} around Slave Lake and Swan Hills, and 0.3 km^{-2} around Whitecourt and Fox Creek. Large fires ($\geq$200 ha) have occurred within 1 km of Slave Lake and Swan Hills, and within 13 and 27 km of Fox Creek and Whitecourt respectively. Individual large fires in the area have exceeded 100 000 ha.

Data

We derived land cover-type data and structure locations from photo-interpretation of digital orthorectified aerial photographs at 1-m resolution. The orthophotos, taken between 1999 and 2002, were acquired from Alberta Sustainable Resource

Development and were interpreted by a skilled technician. Structure locations were digitised, excluding small outbuildings and detached residential garages. We classified the built environment as locations with structures and any immediately adjacent areas including residential lawns, streets, parking lots, and managed vegetation such as manicured parks. Classification decisions were supported by reference to property lines, municipal maps, consultation with local officials, and field visits. The built environment therefore encompassed not only structures, which are a primary concern in community protection planning, but also other valued features that occur nearby, such as outdoor recreation infrastructure, and electrical and communications infrastructure.

Areas that contained vegetation were classified according to the Canadian Fire Behaviour Prediction (FBP) System fuel types (Forestry Canada Fire Danger Group 1992). No attempt was made to classify individual trees, shrubs, or landscaping vegetation within the built environment, as these fuels generally do not represent primary wildfire ignition sources. Water and non-fuel areas were also classified. This exercise took ~1 week per community and distinguished fuel patches as small as 25 m^2. The land cover inventory was then converted to a raster at a resolution of 5 m and was subsequently verified and updated through field visits to areas where the classification was uncertain and through expert-opinion consultation with local fire management staff.

Analysis

We sought to map areas in the built environment located within the range of potential ignitions generated from nearby combustible vegetation and to rate the degree of exposure to these potential ignition sources. The degree of ignition exposure was calculated for each point in the built environment as the proportion of surrounding land cover that contained vegetation capable of generating ignitions. A moving window routine with a radius that varied according to the maximum range of the ignition process under consideration was used to derive exposure ratings. The proximity of a location to the ignition source will determine whether it will be exposed to all or some of the possible ignition types (convection, radiant heat, firebrands, or spotting). Because ignition from convection, or direct contact with flames, occurs at a fine spatial scale, we did not consider this ignition source in our assessment and address only exposure to radiant heat sufficient to cause ignitions and exposure to vegetation conducive to producing short- and longer-range spotting.

We identified fuels of concern in the landscape surrounding each community that were capable of generating any of the ignition processes under investigation (radiant heat, short-range spotting, longer-range spotting). These fuels included grass, conifer, and mixedwood fuels corresponding to the FBP System fuel types: C-1 (spruce–lichen woodland), C-2 (boreal spruce), C-3 (mature jack or lodgepole pine), C-4 (immature jack or lodgepole pine), C-7 (ponderosa pine–Douglas-fir), O-1 (grass), and M-2 (boreal mixedwood). We did not classify mixedwood fuels based on the percentage of conifer composition. Deciduous forests (aspen), water, and non-fuel areas were not considered fuels of concern. Non-fuel areas corresponded to features such as non-structural industrial facilities; recently cleared land consisting of bare rock or soil; wetland, marshes, or beaches; seismic lines, roads, and highways; and managed grassland, including agricultural fields, playing fields, and airport strips.

We identified critical distances associated with each of the ignition processes under consideration (radiant heat, short-range spotting, longer-range spotting), given the fuel types of concern surrounding the four communities. These distances can be expected to vary over time and across an area depending on the types of vegetation present and assumptions about expected fire intensity, topography, and wind conditions. Generalisations are therefore used to relate the most influential factors to broadly representative fire behaviour outcomes. Following Cohen (2004), we considered ignition from radiant heat unlikely at distances greater than 30 m, assuming flame conditions associated with an intense crown fire 20 m in height, 50 m across, and actively burning for 1 min. Short-range spotting is generally thought to occur at distances less than 100 m from the ignition source (e.g. Alexander *et al.* 2004). Longer-range spotting has been documented at distances of 200–1600 m from high-intensity forest fires in fuels similar to the boreal conifer or mixedwood fuel types that occur around our four communities (Table 1).

Kiil *et al.* (1977) reported a maximum spotting distance of 1900 m among observations of 2060 forest fires that occurred in Alberta between 1965 and 1969. Fuel type and weather conditions associated with this maximum spotting distance were not reported, but the average maximum spotting distance of 300 m was associated with windspeeds greater than 40 km h^{-1}. Observations of spotting distances have also been documented in unpublished fire case studies completed for the Wildfire Behaviour Specialist Course sponsored by the Canadian Interagency Forest Fire Centre (see Alexander and Thomas 2003 for a description of the case-study reporting guidelines for this course). We identified 13 observations specific to the fuel types surrounding our four communities. In these 13 cases, spotting distances ranged from 100 to 1000 m, with an average of 376 m. A retrospective assessment of house losses as a function of the shortest distance from adjacent continuous bushlands in Australia (Chen and McAneney 2004) indicated that most losses occurred at distances less than 400 m, despite the potential for spotting up to several kilometres, which suggests that observations of extreme spotting distances are not necessarily relevant for guiding wildland–urban interface assessments of the built environment.

Based on observations of spot-fire distances in Canada and Australia, we chose a critical distance of 500 m for exposure to longer-range spotting. Although spotting can occur at much longer distances, firebrand densities are known to decline exponentially with increasing distance from the ignition source (Porterie *et al.* 2005) and very long spotting distances are relatively uncommon events that are known to be associated with very extreme conditions. For example, the observed spotting distance of 1600 m in Alberta (Table 1) was recorded at a time when wind gusts on the fire were estimated at 74 km h^{-1} (Alberta Sustainable Resource Development 2001).

We used Albini's (1979) predictive models of maximum spotting distance to verify that our assumptions of 100- and 500-m critical short- and longer-range spotting distances were reasonable. These models are not considered representative of

Table 1. Maximum observed spotting distances in conifer or mixedwood fuels

Maximum spotting distance (m)	Fuel types present	Fire name and location	Source
400	Predominantly jack pine	Mack Lake Fire, Michigan, USA	Simard *et al*. (1983)
500	Jack pine	Brereton Lake Fire, Manitoba, Canada	Hirsch (1989)
1000	Jack pine, black spruce	Red Lake #7, Ontario, Canada	Stocks and Flannigan (1987)
200–1600	Boreal spruce, mixedwood	Chisolm Fire, Alberta, Canada	Alberta Sustainable Resource Development (2001)

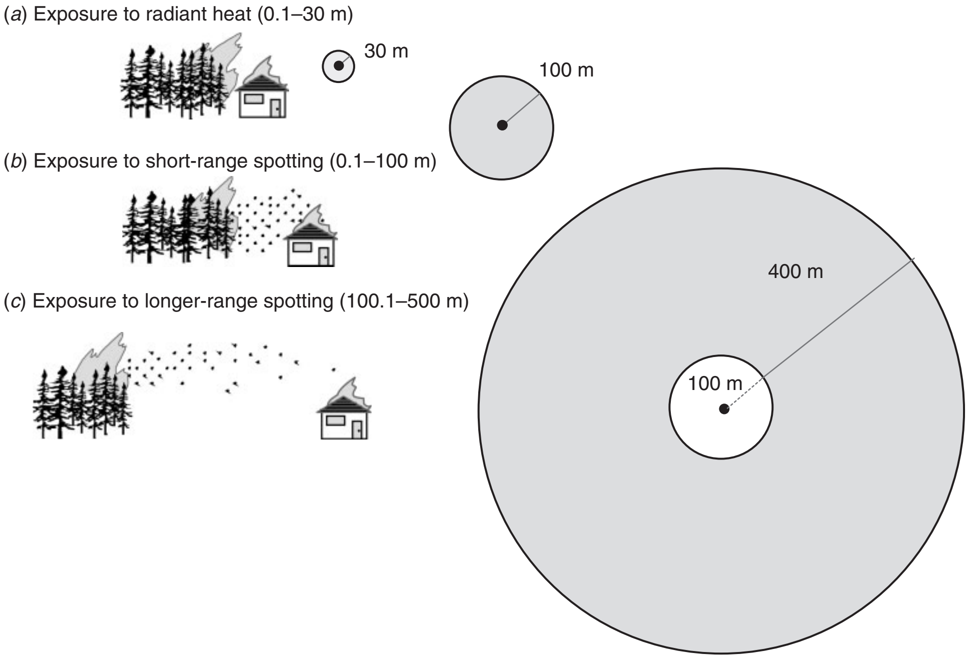

Fig. 2. Ignition processes and corresponding scale of the circular assessment window used to calculate three exposure ratings (*a*, *b*, *c*) for each 5 × 5-m grid cell located in the built environment. Exposure ratings are equal to the proportion of the shaded area within each circular assessment window that contains fuels of concern.

situations capable of producing extreme spotting distances. If we assume firebrands are generated under relatively light winds (7 km h^{-1}) from a cluster of three torching lodgepole pine trees, each 19 m in height and 20 cm in diameter, the maximum spotting distance predicted by Albini (1979) is 113 m. If this scenario is changed to consist of a cluster of 10 torching lodgepole pine trees under high winds (25 km h^{-1}), the maximum spotting distance increases to 531 m. These two scenarios are roughly consistent with conditions we expect to be associated with short-range spotting and wind-driven crown fires that produce longer-range spotting, which suggests that our 100 and 500 m critical distances are reasonable assumptions.

For each 25-m^2 grid cell characterised as the built environment, we rated levels of ignition exposure by calculating the proportion of land cover within each critical ignition distance (0.1–30, 0.1–100, and 100.1–500 m) that contained fuel-types of concern (Fig. 2). For the purposes of our analysis, we grouped all fuels of concern together; however, in cases where ignition processes differ markedly among the fuel types present, individual critical distances could be developed for specific fuel types. Because grass fires are not conducive to longer-range spotting, exposure to this ignition process was limited to conifer and mixedwood fuels. Exposure ratings were calculated with the PLAND metric in *FRAGSTATS*, version 3.3 (McGarigal *et al*. 2002) and the spatial analyst toolset in *ArcGIS*. Results were mapped individually for each ignition process using four equal exposure classes: low (>0–0.15), moderate (0.15–0.30), high (0.30–0.45), extreme (>0.45). Results were also combined to produce an overall wildland–urban interface map that identified four zone types based on the maximum exposure classification associated with the location and the number of ignition processes rated at that exposure level: low or moderate exposure to one or more ignition processes (WUI zone I); high or extreme exposure to one ignition process (WUI zone II); high or extreme exposure to two ignition processes (WUI zone III); and high or extreme exposure to all three ignition processes (WUI zone IV).

To explore how ignition exposure is influenced by the morphology of the built environment, we repeated our analysis using a selection of four hypothetical community shapes (Fig. 3) that were among the set of standard urban forms described by Bierwagen (2005) and adapted from Snellen *et al*. (2002). Each shape (circular, square, rectangle, and lobed) covered an area of

Fig. 3. Urban shapes used to evaluate how exposure to ignition sources is influenced by the morphology of the built environment. Selected from those presented by Bierwagen (2005), adapted from Snellen *et al*. (2002).

Table 2. Land cover composition within a 500-m buffer zone surrounding the built environment, by community
Land-cover types for vegetated areas were classified according to the fuel types of the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992)

Land cover type	Land cover composition (%)			
	Fox Creek	Swan Hills	Slave Lake	Whitecourt
Spruce–lichen woodland (C-1)	1.1	1.1	1.3	1.1
Boreal spruce (C-2)	7.2	41.5	3.5	5.7
Mature jack or lodgepole pine (C-3)	–	10.1	–	3.9
Immature jack or lodgepole pine (C-4)	–	0.3	–	–
Ponderosa pine–Douglas-fir (C-7)	–	–	–	0.5
Boreal mixedwood (M-2)	10.7	7.6	6.6	16.9
Grass (O-1a/b)	13.2	13.0	43.2	25.0
Aspen (D-1)	45.2	8.3	10.9	13.4
Non-fuel	19.5	17.9	20.3	24.8
Water	3.0	0.1	14.2	8.8
Total fuels of concern (radiant heat and short-range spotting)	32.2	73.6	54.6	53.1
Total fuels of concern (longer-range spotting)	19	60.6	11.4	28.1

175 ha and was imbedded in a landscape consisting of a uniform coverage of fuels of concern.

Fuel treatment case study

We used our wildland–urban interface assessment results to evaluate a fuel-management plan developed for the community of Swan Hills. The purpose of fuel treatments in fuels capable of producing high-intensity fires with crown involvement is to reduce fire behaviour potential to a surface fire and to minimise the potential for crown involvement, such that longer-range spotting would be unlikely (Agee and Skinner 2005). Spatial coverage of proposed fuel treatments for 2 years was obtained from Alberta Sustainable Resource Development. Treatments planned for Year 1 involved 113 ha with 92% in the boreal spruce fuel type (C-2). Year 2 treatments involved 143 ha with 80% in the boreal spruce fuel type and 15% in the mature lodgepole pine fuel type (C-3). Because most of the fuel-treatment area is positioned at a distance from the built environment, we did not expect these treatments to affect exposure to ignition from radiant heat or short-range spotting. We assumed that an effective fuel-treatment regime, through thinning, surface fuels reduction, reduction of the crown base height, or prescribed burning activities would render the area incapable of generating longer-range spotting. To assess the impact of the fuel treatments on exposure to longer-range spotting, we converted the fuel-treatment areas from their baseline state as a fuel of concern (conifer or mixedwood) to a benign state and then compared baseline exposure to longer-range spotting with exposure ratings recalculated after proposed Year 1 and Year 2 fuel treatments.

Results

All four communities had a significant proportion of non-fuel areas (18–25%) within a 500-m buffer zone around the built environment (Table 2). The proportion of land cover consisting of flammable forest vegetation varied by community. Swan Hills had the highest proportion of fuels of concern (61–74%) surrounding the community, whereas substantial areas surrounding Fox Creek and Slave Lake (45–89%) were not a concern.

Ignition exposure levels varied within and between communities (Table 3). Exposure to ignition from radiant heat (Fig. 4) was highest for Whitecourt, where 11% of the area classified as the built environment had high or extreme exposure levels. Small amounts (2–7%) of the built environment in Swan Hills, Slave Lake, and Fox Creek had high or extreme exposure to ignition from radiant heat. Almost all structures (98–99%) within these

Table 3. Proportion of structures and land-cover area within the built environment with a given exposure rating by ignition process (*a*, *b*, *c*), and by community

	Proportion of structures				Proportion of land-cover area			
	Fox Creek	Slave Lake	Swan Hills	Whitecourt	Fox Creek	Slave Lake	Swan Hills	Whitecourt
(*a*) Exposure to ignition from radiant heat (conifer, mixedwood, and grass fuels within 30 m)								
Nil (0)	0.98	0.95	0.89	0.89	0.93	0.87	0.85	0.76
Low (>0–0.15)	0.01	0.03	0.10	0.09	0.04	0.05	0.08	0.08
Moderate (0.15–0.30)	0.00	0.01	0.01	0.01	0.02	0.02	0.03	0.05
High (0.30–0.45)	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.03
Extreme (>0.45)	0.00	0.01	0.00	0.00	0.01	0.05	0.01	0.08
(*b*) Exposure to ignition from short-range spotting (conifer, mixedwood, and grass fuels within 100 m)								
Nil (0)	0.83	0.80	0.52	0.57	0.71	0.64	0.46	0.46
Low (>0–0.15)	0.14	0.12	0.29	0.25	0.20	0.19	0.31	0.27
Moderate (0.15–0.30)	0.03	0.05	0.16	0.12	0.06	0.08	0.15	0.13
High (0.30–0.45)	0.00	0.01	0.03	0.05	0.02	0.05	0.07	0.08
Extreme (>0.45)	0.00	0.01	0.00	0.01	0.01	0.05	0.01	0.07
(*c*) Exposure to ignition from longer-range spotting (conifer and mixedwood fuels between 100.1 and 500 m)								
Nil (0)	0.38	0.57	0.00	0.48	0.28	0.51	0.00	0.32
Low (>0–0.15)	0.56	0.41	0.21	0.27	0.59	0.44	0.18	0.45
Moderate (0.15–0.30)	0.05	0.02	0.48	0.14	0.12	0.05	0.48	0.15
High (0.30–0.45)	0.00	0.00	0.24	0.11	0.01	0.00	0.28	0.08
Extreme (>0.45)	0.00	0.00	0.07	0.00	0.00	0.00	0.05	0.01

three communities had nil or low exposure to ignition from radiant heat. Ignition from radiant heat was not a concern for Fox Creek.

Exposure to ignition from short-range spotting (Fig. 5) was highest for Whitecourt, followed by Slave Lake and Swan Hills. In all three of these communities, 8% or more of the built environment had high or extreme exposure levels. Of the structures, 19% in Swan Hills and 17% in Whitecourt had moderate or high exposure to ignition from short-range spotting.

Exposure to longer-range spotting (Fig. 6) was highest in Swan Hills: 32% of the built environment and 31% of structures had high or extreme exposure ratings. Moderate exposure to longer-range spotting occurred for 48% of the built environment and 48% of structures in Swan Hills. In Whitecourt, 25% of structures had moderate or high exposure to longer-range spotting. Longer-range spotting was not a significant factor for Slave Lake and Fox Creek. The magnitude of the difference in moderate to high exposure ratings between Whitecourt and Fox Creek (Table 3*c*) is not proportional to the difference in the amount of fuels of concern surrounding these two communities (Table 2), which indicates that factors other than fuel quantity influence exposure ratings, such as the size and arrangement of fuel patches in relation to the unique morphology of the built environment.

The isolated patch of elevated exposure ratings in the southeast area of Fox Creek (Fig. 5) is a good example of an occluded interface zone, or an island of flammable vegetation imbedded within the built environment. In this case, the 2-ha area is composed of boreal spruce (C-2) and boreal mixedwood (M-2) fuel types and results in elevated exposure to short-range spotting. Elevated exposure levels embedded within the community of Whitecourt reflect the presence of many occluded patches, 0.16 to 2.2 ha in size, consisting primarily of mature lodgepole pine (C-3 fuel type). In total, Whitecourt has 97 ha of occluded interface areas that contain fuels of concern. These areas result in elevated exposures to radiant heat and short-range spotting. In contrast, Swan Hills has generally continuous belts of progressively increasing exposure levels as you move from the centre of the community out towards the boundary of the built environment, which reflects the minimal presence of occluded interface areas containing fuels of concern (9 ha) and the relatively large and continuous areas containing fuels of concern that surround the community.

Large parts of the built environment in Slave Lake (40%), Fox Creek (25%), and Whitecourt (22%) have no exposure to any of the three ignition processes (Fig. 7). In Swan Hills, the entire built environment has some level of exposure. Fuel treatments were effective in altering exposure levels to longer-range spotting in this community (Fig. 8, Table 4). Compared with baseline conditions, Year 1 fuel treatments resulted in a 61% decrease in the number of structures with high or extreme exposure to longer-range spotting and a corresponding 37% decrease in the area of the built environment with these exposure ratings. The addition of Year 2 fuel treatments resulted in relatively minor improvements, which suggests that Year 2 treatments may not be useful for reducing exposure to longer-range spotting.

Our assessment of four hypothetical communities with different morphological forms (circular, square, rectangle, lobed) revealed that circular and square communities will have lower exposure levels than rectangular or lobed communities. The area of the lobed community with high or extreme exposure to radiant heat was 2.3 times greater than the area exposed in a circular community and corresponded to the difference in perimeter/area ratio, which was 2.4 times greater for the

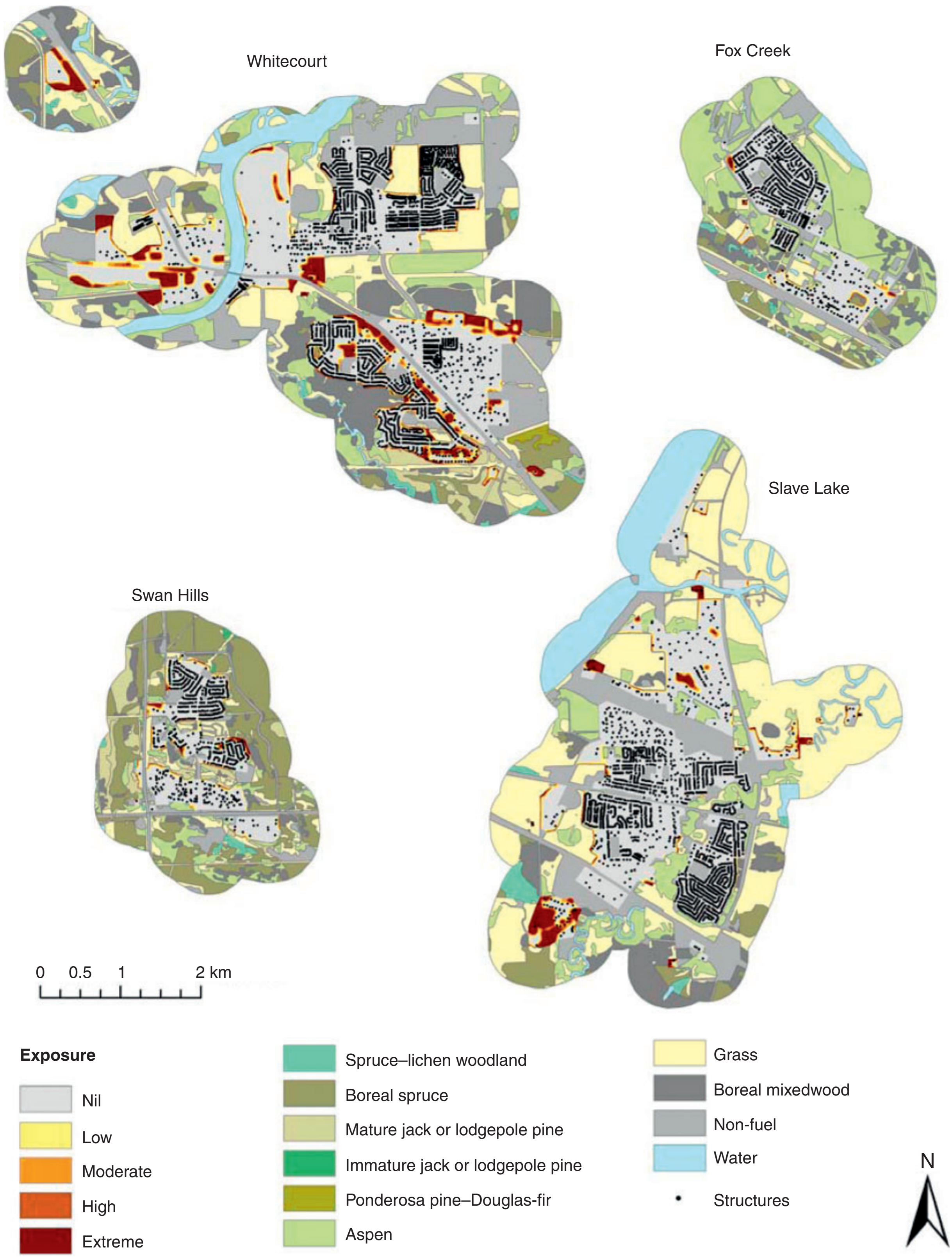

Fig. 4. Spatial variation in exposure to ignition from radiant heat across the built environment, by community.

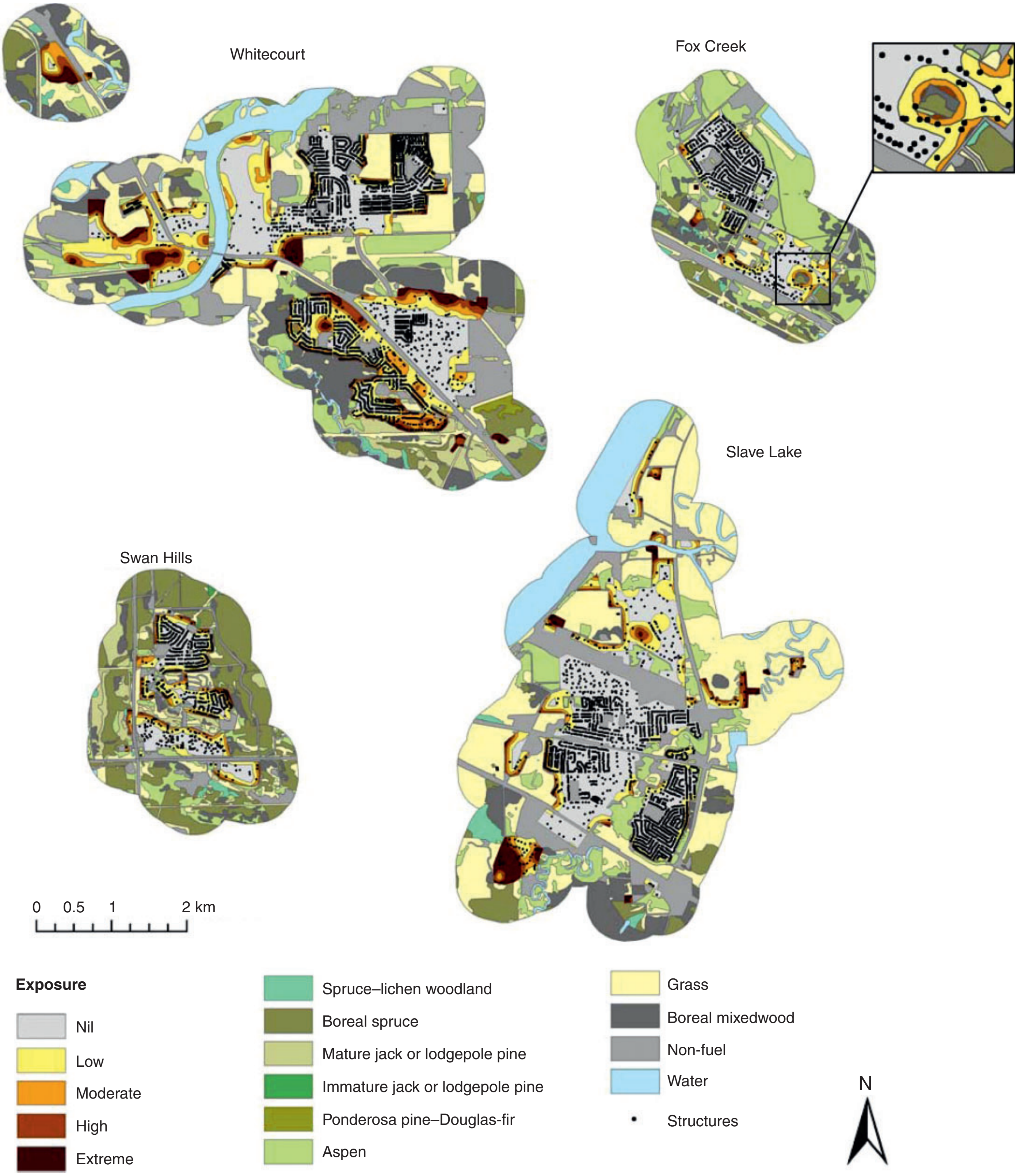

Fig. 5. Spatial variation in exposure to ignition from short-range spotting across the built environment, by community.

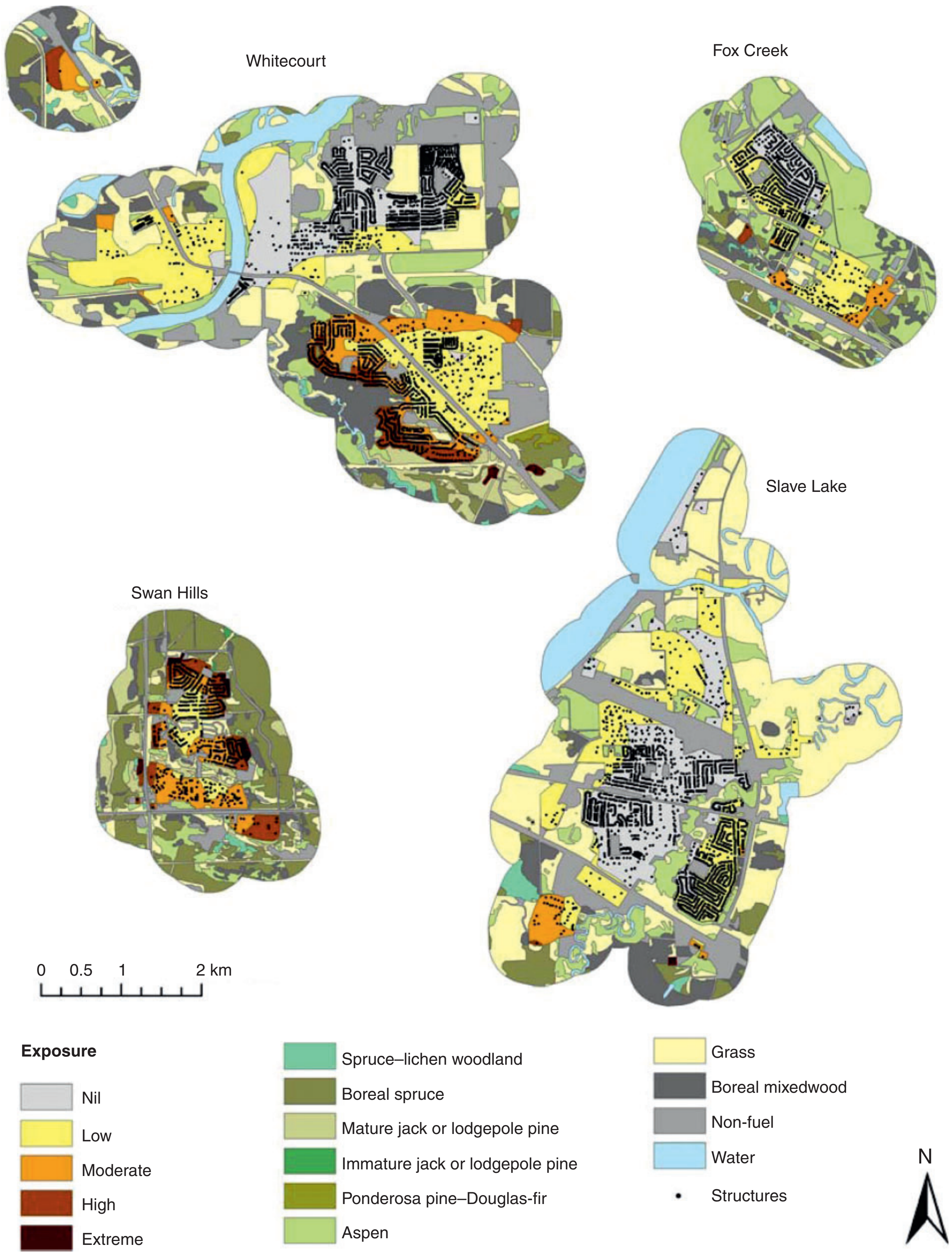

Fig. 6. Spatial variation in exposure to longer-range spotting across the built environment, by community.

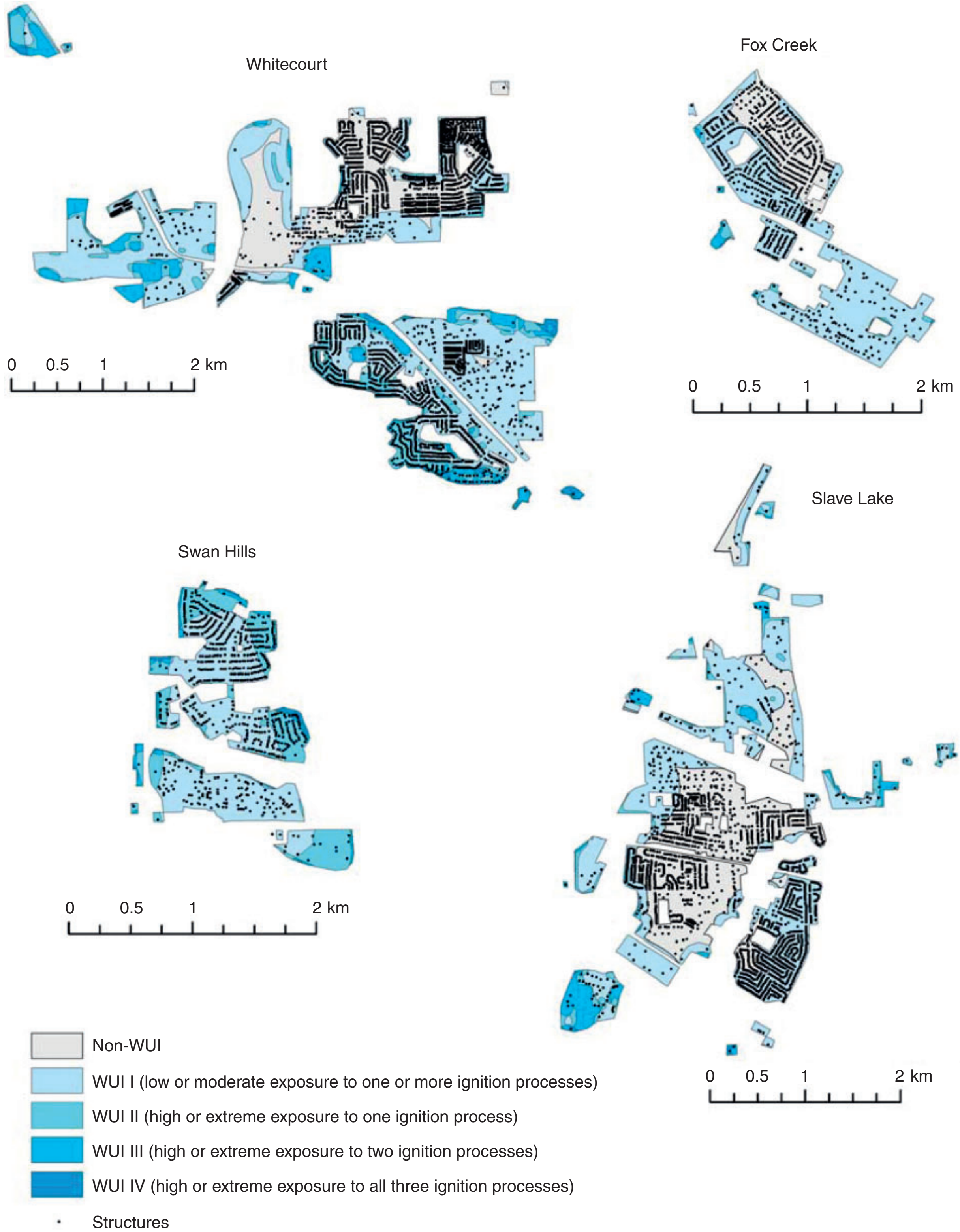

Fig. 7. The built environment and its portion classified as wildland–urban interface (WUI) zones I to IV, by community.

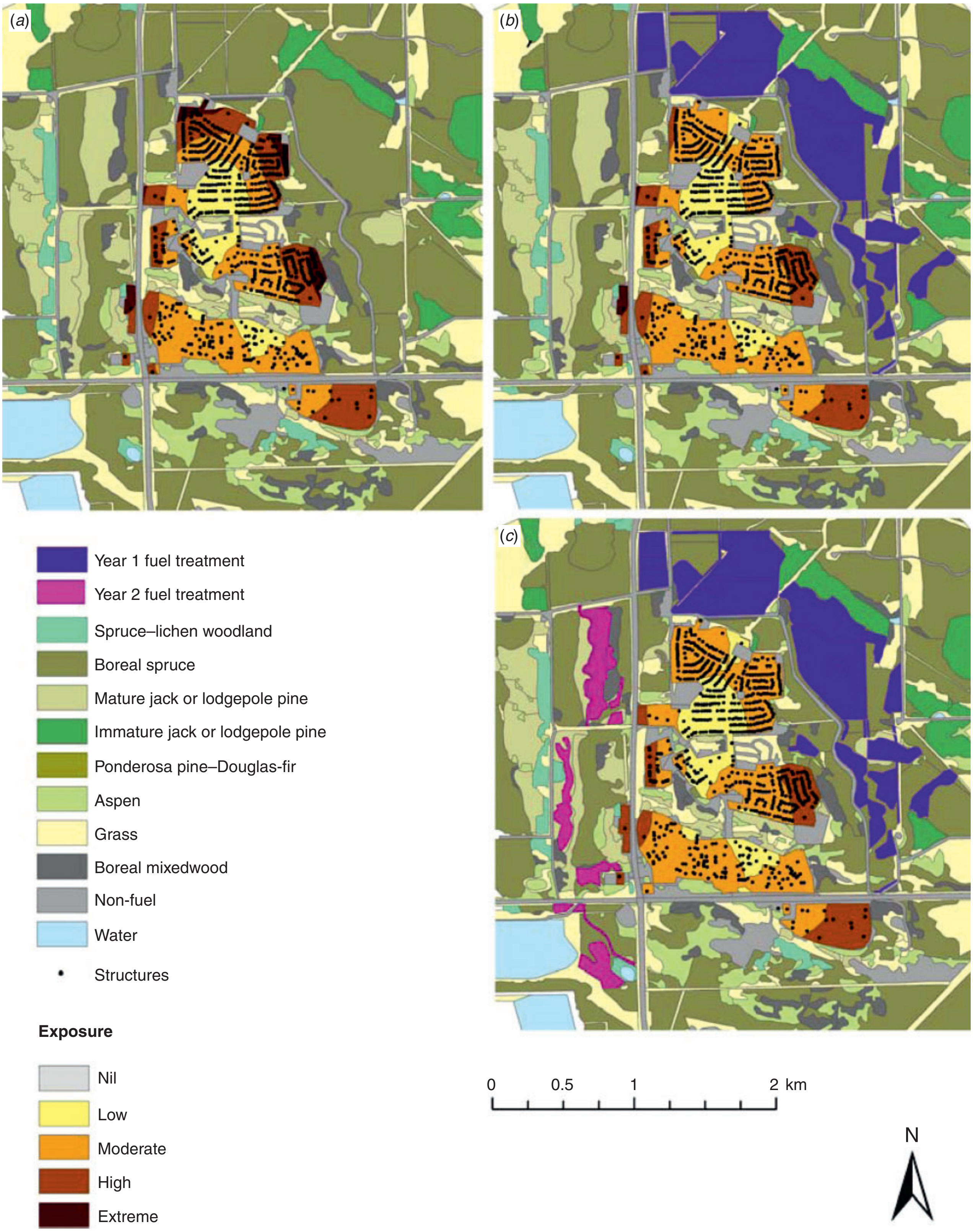

Fig. 8. Spatial variation in exposure to longer-range spotting within the built environment of Swan Hills for (*a*) baseline conditions; (*b*) conditions after Year 1 fuel treatments; and (*c*) conditions after Year 1 and Year 2 fuel treatments.

Table 4. Proportion of structures and land-cover area within the built environment of Swan Hills with exposure to longer-range spotting after Year 1 and Year 2 fuel-treatment scenarios compared with baseline conditions, by exposure class

Exposure class	Proportion of structures			Proportion of area		
	Baseline	Year 1	Year 2	Baseline	Year 1	Year 2
Nil (0)	0.00	0.00	0.00	0.00	0.00	0.00
Low (>0–0.15)	0.21	0.23	0.24	0.18	0.20	0.21
Moderate (0.15–0.30)	0.48	0.65	0.65	0.48	0.59	0.61
High (0.30–0.45)	0.24	0.12	0.11	0.28	0.20	0.18
Extreme (>0.45)	0.07	0.00	0.00	0.05	0.01	0.00

lobed community. Perimeter/area ratios calculated for the four communities provided some insight into how community morphology influences exposure ratings. The perimeter/area ratio was highest for the community of Swan Hills where 100% of the built environment was classified as the wildland–urban interface (Fig. 7). Fox Creek had among the lowest overall exposure ratings (Table 3) but the second highest perimeter/area ratio, which highlights the importance of accounting for the type and arrangement of fuels of concern surrounding the built environment in combination with community morphological form.

Discussion

We considered locations within the built environment to be part of the wildland–urban interface if they were located within the range of potential ignitions generated from nearby combustible vegetation. By combining information about fire behaviour processes with buffer mapping in a geographical information system, we mapped the extent of the wildland–urban interface, and the associated degree of ignition exposure, for four communities in Alberta, Canada. Ignition processes of concern differed among the four communities included in our assessment. For Swan Hills, exposure levels to short- and longer-range spotting were most concerning. Exposure ratings for Slave Lake indicated that radiant heat and short-range spotting are the primary concerns in that community. Whitecourt had elevated exposures for all ignition processes considered, whereas Fox Creek exhibited consistently low exposure to these ignition processes. These results could be used to inform community-specific strategies for reducing fire susceptibility and for prioritising communities, and areas within communities, for mitigation action.

We combined the individual ratings of exposure to each ignition process (radiant heat, short-range spotting, longer-range spotting) to produce an overall map of the extent of the wildland–urban interface, and the degree of ignition exposure, for each community. Zones were used to map wildland–urban interface conditions based on the number of ignition processes that affect a given area and the associated levels of ignition exposure. Areas with high or extreme levels of exposure to multiple ignition processes indicate priority locations that will require site-level assessments and multi-faceted mitigation strategies.

Of the four communities included in our assessment, Swan Hills was the only community where the wildland–urban interface covered the entire area of the built environment. Significant quantities of high-flammability conifer and mixedwood fuels lie within a 500-m buffer zone around this community, and these fuels occur in relatively large, intact patches that collectively cover an area more than twice the size of the built environment. Unlike the other communities in our analysis, Swan Hills has experienced multiple wildfire-induced evacuations (unpubl. data, Canadian Forest Service Northern Forestry Centre, Edmonton, AB). Our evaluation of new fuel treatments proposed for this community indicated that significant reductions in ignition exposure can be achieved if potential sources of longer-range spotting are eliminated over an ~113-ha area to the north and east of the built environment. When we simulated fuel treatments in this area, a total of 133 structures that originally had high or extreme exposure ratings were reclassified as having moderate or low exposure to longer-range spotting (i.e. for every 0.9-ha treated, one structure was eliminated from the high or extreme exposure class).

Our results indicated that the spatial pattern of areas with elevated ignition exposure within the built environment reflects not only the amount of fuels of concern that occur in the area surrounding the built environment, but also the size and arrangement of fuel patches in relation to the unique morphology of the built environment and the occurrence of occluded interface zones within the built environment. For example, the patchy pattern of extreme exposure areas in Whitecourt appears to reflect the discontinuous, patchy structure of fuels of concern both within and surrounding the community. Information on the spatial pattern of elevated ignition exposure areas across a community is important for strategic planning purposes. A community like Whitecourt with a fine-grained pattern of high- and extreme-exposure areas will represent a more challenging public education and communications problem than Swan Hills where large portions of neighbourhoods have uniform ignition exposure and residents can be expected to respond to a single public education message targeting the entire area.

Structures are a primary concern in community protection planning and we reported the number of structures associated with a given exposure class. Exposure ratings could also be related to other features distributed throughout the built environment, such as critical electrical or communications infrastructure, or roads identified as critical evacuation routes. Maps of ignition exposure ratings are powerful visual images that could be used to motivate the public to participate in proactive mitigation activities and for counteracting misconceptions of fire risk known to exist among residents in some communities. For example, Winter and Fried (2000) found that residents in Michigan held a perception that forest fires caused random destruction, which led them to believe that mitigation activities were futile. Talberth *et al*. (2006) investigated the impact of risk-map information on homeowners' decisions to purchase insurance and undertake mitigation activities and concluded that knowledge of fire risk levels resulted in more efficient allocation of resources.

The shape or morphology of the built environment alone will influence ignition exposure levels, as indicated by the results of our assessment of four hypothetical communities composed of different shapes (circle, square, rectangle, lobed). Our results indicated that communities with a complex lobed shape or elongated rectangle shape have larger perimeter/area ratios and will have inherently higher levels of exposure when fuel conditions are held constant, which suggests that it may be possible to use our method to derive design criteria for new developments in wildland–urban interface areas.

Wildland–urban interface mapping of the built environment should, ideally, be part of a suite of assessments conducted at multiple scales. In a separate study (Beverly *et al*. 2009), we assessed fire susceptibility across the broader landscape surrounding the four communities assessed in the present study. In that study, we used a simulation modelling approach that involved repeated simulations of the ignition and spread of fires across the landscape as a means of assessing which areas are most likely to burn (see also Farris *et al*. 2000; Carmel *et al*. 2009). This type of landscape simulation modelling is useful for incorporating multiple fire environment and fire regime characteristics, such as fire weather and ignition patterns, that combine to influence fire susceptibility in an area, and for identifying broad fire susceptibility zones. Because landscape assessments must include large areas to adequately model fire regime processes, results are limited to units of analysis that would obscure the interaction between fuel patterns and the morphology of the built environment that we have captured with our community/neighbourhood assessment. For example, both Preisler *et al.* (2004) and Dickson *et al*. (2006) mapped fire susceptibility at a 1-km resolution compared with the 5-m resolution used in our present study. Landscape-level assessments are, however, well suited to identifying communities of concern. Our landscape fire susceptibility assessment (Fig. 7; Beverly *et al*. 2009) indicated that the community of Swan Hills is adjacent to a high landscape fire susceptibility zone and in close proximity to an extreme susceptibility zone, which makes the results of our wildland–urban interface assessment for this community particularly concerning. In contrast, landscape susceptibility surrounding the community of Whitecourt was relatively low.

In northern forest ecosystems like our study area, it may be prudent to consider the results of a wildland–urban interface ignition exposure assessment independently of the broader landscape susceptibility assessment that characterises the likelihood or probability of fires occurring in the landscape surrounding the communities. Fires that prompt wildland–urban interface events in these regions are relatively rare, such that historical weather regime and fire regime data used to parameterise landscape simulation models may not necessarily reflect the future potential for wildland–urban interface fire events, particularly given changing conditions associated with global warming and landscape vegetation. In the case of low-probability, high-consequence events, community/neighbourhood assessments like ours, which are based on an understanding of fundamental fire processes, may be more informative than traditional risk assessment methods that characterise fire probabilities based on historical data.

We did not attempt to assess the likelihood that materials in the built environment will ignite as a result of firebrand impact. Although predictive models of fire ignition potential in fuel beds representative of those found in the built environment have been developed (Steward *et al*. 2003; Manzello *et al*. 2006*a*, 2006*b*), the presence or absence of receptive fuel beds is more appropriately addressed in fine-scale assessments that involve site visits. Results of our analysis could be used to focus site assessments of ignition receptivity in those areas with the highest levels of exposure to potential ignition sources.

Our assessments of the communities of Fox Creek, Slave Lake, Swan Hills, and Whitecourt were based on the exposure of the built environment to relevant ignition processes (radiant heat, short-range spotting, and longer-range spotting) and the resulting maps provide a spatial delineation of the boundaries of the wildland–urban interface that include a relative rating of ignition exposure levels. Because we are mapping wildfire entry points into the built environment, we do not consider house-to-house ignitions. Ideally, the implications of our results should be considered in combination with assessments conducted at other spatial scales as part of a comprehensive wildland–urban interface risk assessment. In addition to landscape-level assessments that can provide information about the likelihood of wildfires occurring in fuels of concern around a community and site-level assessments that can be used to evaluate the likelihood that locations within the built environment will be receptive to ignitions once they occur, factors associated with fire suppression capability, such as access and resources, and community coping capacity should also be considered as part of a comprehensive wildland–urban interface risk assessment.

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