Mapping Canadian Wildland Fire Interface Areas

by

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Abstract

Although wildland fires are a beneficial ecosystem process, they can also cause destruction to human-built structures and infrastructure, as evidenced by disasters such as the Fort McMurray fire in 2016 and the Slave Lake fires in 2011. This type of destruction occurs in the "wildland-urban interface" (WUI), which are areas where homes or other burnable community structures meet with or are interspersed within wildland fuels. In order to mitigate destructive WUI fires, basic information such as the location of these areas is required. Unfortunately, Canada does not have a national scale, high-resolution WUI map for use in research or fire management, which hinders our ability to study fires in WUI areas. Therefore, this study focused on defining and mapping the WUI for the national area of Canada, and analysed their spatial distribution and relationships with fuels, structures, and fires. Furthermore, two additional national maps were produced and analysed: a "wildland-industrial interface" (WII) map and an "infrastructure interface" map. These additional maps focus on the interface of wildland fuels with industrial structures (e.g. oil and gas or mining structures) for the WII, or with infrastructure values (e.g. transmission lines, railways, or roads) for the infrastructure interface. This study presents the first maps of these two interface types for anywhere in the world. Industrial structures and infrastructure are not traditionally defined as part of the WUI, but may require protection from fires and are important emerging issues. All three interface types (WUI, WII, and infrastructure interface) were defined as areas of wildland fuels which are within a variable-width buffer (maximum distance: 2400 m) from potentially vulnerable structures or infrastructure. Nationally, it was found that Canada has 32.3 million ha of WUI (3.8% of total national land area), 10.5 million ha of WII (1.2%), and 109.8 million ha of infrastructure interface (13.0%). Interface areas are typically most dense in the southern portion of the country

(with the exception of the prairies and southern Ontario). Provinces with the largest amounts of interface include: Quebec, Ontario, Alberta, and British Columbia. However, the eastern provinces of Nova Scotia, New Brunswick, and Prince Edward Island have the highest densities of interface (interface as % of land area). Interface areas were also found to have higher than average hazardous fuel cover types, but lower than average area burned by wildfire. The results of this study, and in particular the interface maps, provide a baseline for future research, including fire risk mapping, change detection, and future predictions of interface areas. The maps produced in this study also have a wide variety of practical applications, including various topics in wildfire mitigation (e.g. FireSmart and industrial fire regulations), long-term planning (e.g. city planning and insurance), and wildfire decision support (e.g. fire prioritization and risk modelling).

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And finally, to my son Jeffery: thank you for being the ultimate distraction and forcing me to remember that life happens outside of work.

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1 INTRODUCTION

1.1 Wildland Fire

Humans have been referred to as "the planet's keystone species for fire" (Pyne 2013), which is certainly accurate in Canada (Weber and Flannigan 1997). Fire was an essential tool used by Aboriginal peoples in Canada for purposes varying from promoting berry growth to hunting (e.g. driving prey or attracting prey to the food that grows post-burn) (Lewis 1977; Lewis 1982; Pyne 2007; Pyne 2013; McGee *et al.* 2014). As Europeans settled in Canada, fire was used to clear land for agricultural purposes (Pyne 2007; McGee *et al.* 2014). With the industrial revolution, wildfire transformed from being used as a tool to being an opponent, requiring control and suppression (Pyne 2007; McGee *et al.* 2014). Currently, the ecological benefits of fire shaping Canada's natural landscapes are recognized, and suppression activities are carried out when necessary to protect communities or other values (Weber and Stocks 1998; FAO 2007; Pyne 2007; Stocks and Flannigan 2013).

Wildland fire is ubiquitous across Canada; every year, an average of over 7000 wildland fires burn more than 2 million hectares (ha) (CIFFC 2013) (Figure 1-1). Most fires (~65%) in Canada are presently ignited by humans (railways, recreation, power lines etc.) (Weber and Stocks 1998). However, many human-caused fires remain small due to early detection of these fires and aggressive fire suppression, and as a result, the vast majority of area burned (~85%) is from large lightning-caused fires (Weber and Stocks 1998; Stocks *et al.* 2002; Krezek-Hanes *et al.* 2011). Fire suppression activities are primarily carried out to protect human communities and infrastructure, with expenditures reaching up to (or even exceeding) \$1 billion per year (Canadian Council of Forest Ministers 2005; Stocks and Martell 2016). The ecological benefits of fire and the need for fire on the landscape have begun to be recognized, with prescribed burn programs and "let it burn"/"modified suppression"/"appropriate response" policies becoming more prevalent across Canada (Stocks 1993; Stocks and Flannigan 2013; McGee *et al.* 2014; Smith *et al.* 2016). Fire suppression continues to be the default, particularly when human lives or structures are involved.
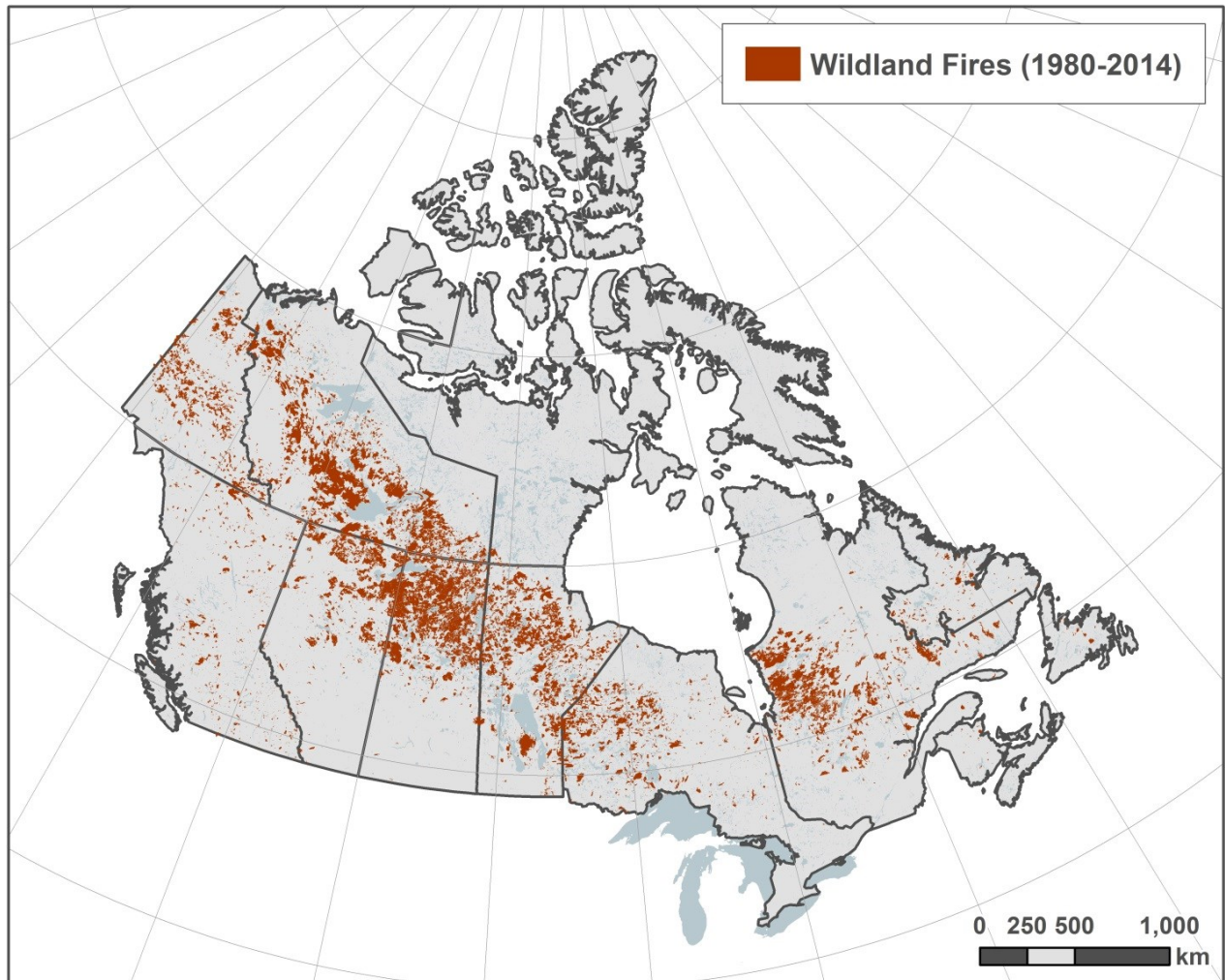
Figure 1-1. National map of area burned by fires 1980-2014.
Fire area burned polygons from Canada's National Fire Database (NFDB) (Canadian Forest Service 2014) for the years 1980-2014.

Though fire suppression is very effective (Cumming 2005; Wotton and Stocks 2006; Martell and Sun 2008; Stocks and Flannigan 2013), not all fires that threaten human-built structures can be stopped (Calkin *et al.* 2014). Inevitably, fire suppression is overwhelmed by a particularly dynamic fire or multiple fires, and structures are lost (Podur and Wotton 2010; Calkin *et al.* 2014). Throughout Canadian history, there are many examples of fires or clusters of fires that have resulted in loss of human life and/or structures (Pyne 2007; Alexander 2010). In more recent years, proactive evacuations of many thousands of people (Wotton and Stocks 2006; Alexander 2010; Beverly and Bothwell 2011) (Figure 1-2) well before fire arrival have meant that only one civilian life has been lost (directly) to wildland fires since 1938 (Alexander 2010; Beverly and Bothwell 2011). Unfortunately, structures do continue to be lost. Though consistent

documentation on structural losses on a national scale is lacking, data compiled by Beverly and Bothwell (2011) (using primarily media and agency reports of evacuations) shows that losses of homes or seasonal homes associated with wildfire evacuations are not entirely uncommon, and are a national issue (Figure 1-2).
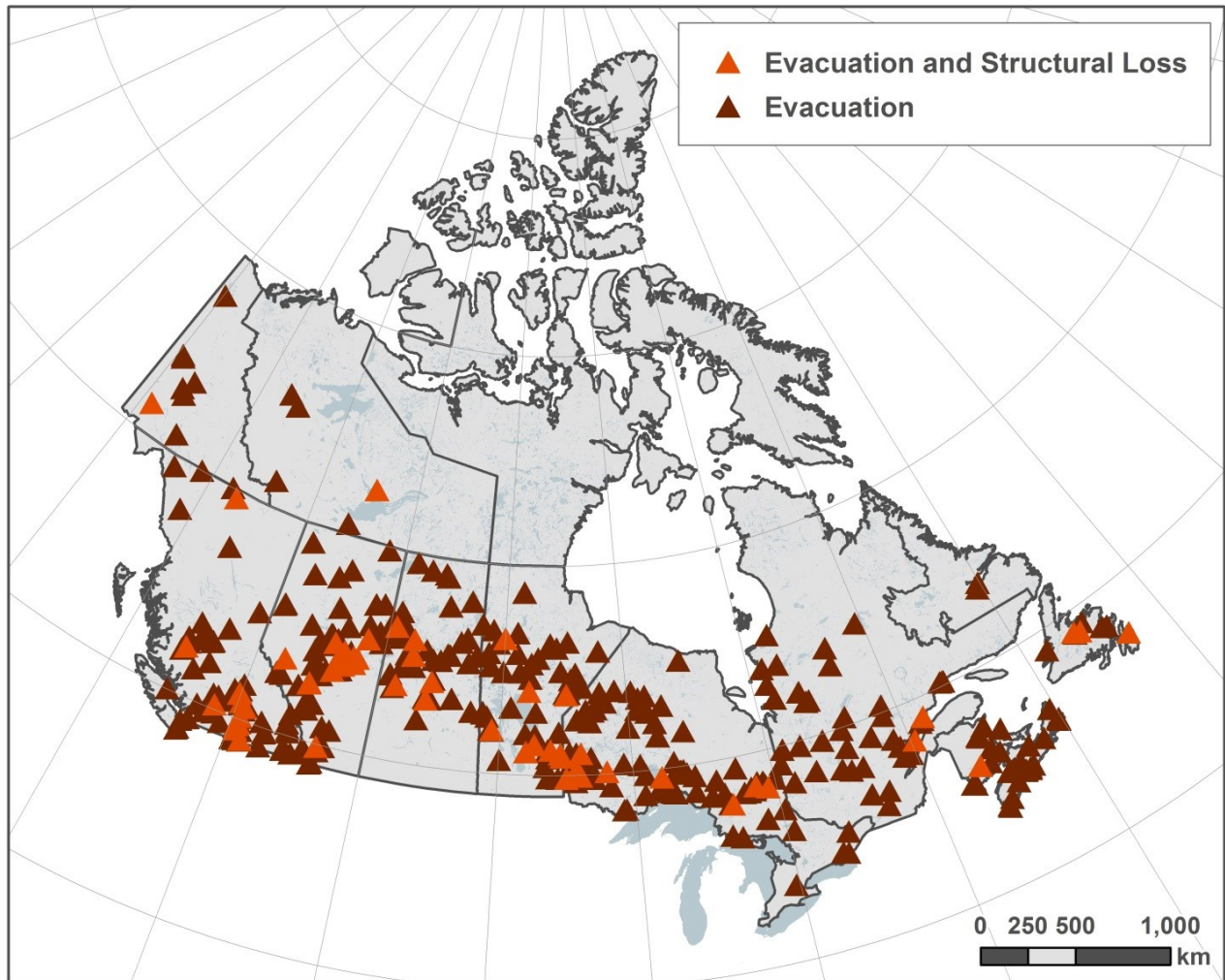
Figure 1-2. Map of evacuations and evacuations with structure loss due to fire 1980-2007. Documented evacuation locations and evacuations with structural losses (of homes or seasonal homes) from 1980-2007 compiled by Beverly and Bothwell (2011). Each evacuation point represents a single evacuation event caused by wildfire which was reported by media or recorded by national or provincial/territorial agencies (with some supplementary data sources); points showing evacuation event with structural loss represents a single evacuation event reported by the media which also had structural loss of one or more homes and/or seasonal homes.

The map in Figure 1-2 was compiled from data from 1980-2007; missing from this map are two more recent fires which are among the most destructive fires in Canadian history. The first fire was in 2011 in Slave Lake, Alberta and surrounding communities where 410 homes and commercial structures were destroyed, along with six apartment buildings, three churches, and

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the government center (Flat Top Complex Wildfire Review Committee 2012; McGee *et al.* 2014). Accounting for only direct costs of suppression, evacuation, insurance, and recovery, brings the cost of the Slave Lake fires to over $1 billion (Flat Top Complex Wildfire Review Committee 2012; McGee *et al.* 2014). The second fire was in May 2016 in Fort McMurray, Alberta where record-breaking evacuations (88,000 people) and structure destruction occurred (~2400 structures destroyed and toxic ash resulted in another 567 homes to be declared unsafe) (Aon Benfield 2016; Husser 2016). The direct costs of this wildfire event are yet to be tallied, but are expected to exceed that of the Slave Lake fires. It has also been projected that this wildfire will likely be the most costly insurable loss in Canada's history (estimated at over $4 billion; exceeding the 2013 southern Alberta flooding and the 1998 Ontario/Quebec ice storm), and will also be among the costliest wildfires in the world (Insurance Bureau of Canada 2015; Aon Benfield 2016). Figure 1-3 show an image of some of the destruction to structures done by the Slave Lake and Fort McMurray fires.

Figure 1-3. Photographs of destruction from wildfires in Slave Lake and Fort McMurray. Post-fire aerial photo of residential areas destroyed by a wildfire that spread into the community of **a)** Slave Lake (2011) and **b)** Fort McMurray (2016). Photo credits: Mike Flannigan / University of Alberta (a), Brian Wiens / Canadian Forest Service (b).

Further indirect costs were incurred from both the Slave Lake and Fort McMurray fires and are more difficult to quantify, so they largely go unaccounted for in cost estimates. These indirect costs can include: loss of timber resources and the cost of reforestation (Peter *et al.* 2006; FAO 2007), disruption of transportation networks and industry (Peter *et al.* 2006; Flat Top Complex Wildfire Review Committee 2012; McGee *et al.* 2014; Aon Benfield 2016; The

Canadian Press 2016), effects on ecosystem services such as water quality and carbon storage (Costanza *et al.* 1998; Peter *et al.* 2006), human health impacts (Peter *et al.* 2006; Kochi *et al.* 2010; Beverly and Bothwell 2011; Reisen *et al.* 2015), loss of recreational use (Peter *et al.* 2006; McCaffrey *et al.* 2012), and climate change effects of greenhouse gas emissions (Bowman *et al.* 2009). Furthermore, there are also a multitude of social impacts associated with the fire, smoke, and evacuation of communities (e.g. loss of cultural values, stress, disruption of daily life) (McFarlane 2006; McGee *et al.* 2014).

1.2   Wildfire vs. Human-Built Structures: the Wildland-Urban Interface

Direct and indirect costs of wildland fires are highest in locations where human settlements are developed in formerly natural areas that are susceptible to wildfires (Moritz and Stephens 2008; Mell *et al.* 2010; Gude *et al.* 2013; Chuvieco *et al.* 2014; Price and Bradstock 2014). The area where homes or other structures meet with or are dispersed within wildland vegetation is known as the wildland-urban interface (WUI). The WUI can take many forms, and can range from a defined line of structures abutting wildland vegetation (generally referred to as "interface" WUI; Figure 1-4a) to scattered or isolated structures amongst the forest ("intermix" WUI; Figure 1-4b) (USDA and USDI 2001)[1]. Having "urban" in the name is somewhat misleading, as many areas that would not be considered an urban area are actually WUI areas. "Urban" can be thought as representing any human-built areas containing homes, cottages, public buildings, or commercial structures.

Managing fire in any community's WUI area is a complex task with high stakes and high pressures (Radeloff *et al.* 2005; Liu *et al.* 2007). WUI fires have the potential to affect many people (Theobald and Romme 2007) and are a very political and contentious issue involving both impacts on and responsibilities of many players, including multiple government agencies and homeowners (Davis 1990; Radeloff *et al.* 2005; Moritz and Stephens 2008; Lein and Stump 2009; McGee *et al.* 2014).

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[1] *A third "type" of interface is occasionally referred to in the literature: the "occluded" interface, which describes a unique situation where an area of wildland fuels are surrounded by human-built structures. For example, an area of forest reserved as a natural area located within a residential area would be considered an occluded interface area. Davis (1990) first referred to the occluded interface as "the isolated interface", but it has since become known as the occluded interface (USDA and USDI 2001).*
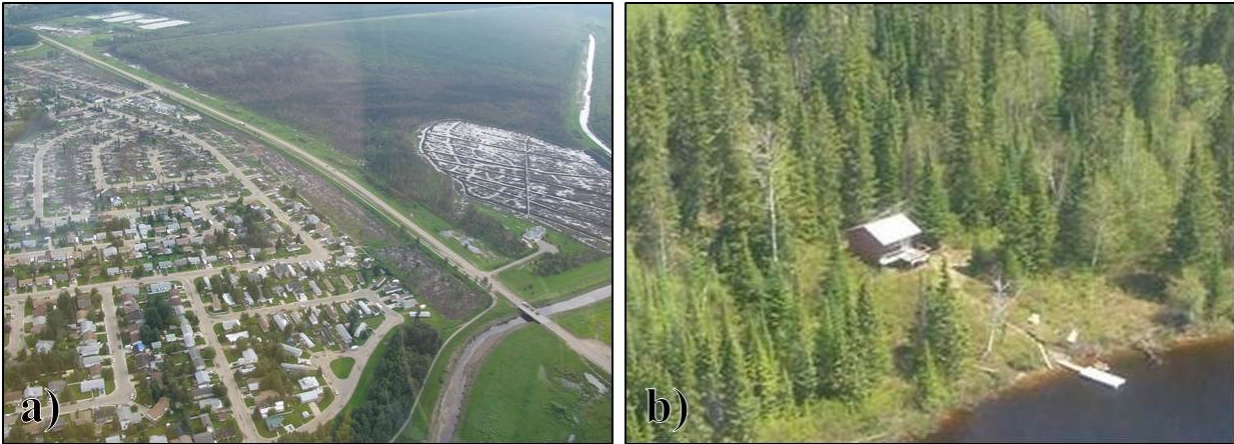
Figure 1-4. Aerial photographs of wildland-urban "interface" and "intermix" situations. Aerial photos depicting wildland-urban interface types: **a)** interface, where human-built structures meet with wildland fuels, and **b)** intermix, where human-built structures are dispersed within wildland fuels. Photo credits: Mike Flannigan / University of Alberta (a), Jeremy Johnston / Ontario Ministry of Natural Resources and Forestry (b).

Fires in the WUI will likely become even more of an issue in the future for two main reasons: 1) increased fire activity due to climate change is predicted for most of Canada (Flannigan *et al.* 2009; Wang *et al.* 2015; Flannigan *et al.* 2016), and 2) there will likely be more WUI area due to changes in human land use (e.g. urban and rural sprawl and increasing recreational land use) (Bollman and Clemenson 2006; Peter *et al.* 2006; FAO 2007; Liu *et al.* 2007; Theobald and Romme 2007). In order to predict, adapt to, or mitigate these changes in the WUI, there must be an understanding of the current situation (specifically, the location and size of the WUI must be known). Unfortunately, in Canada there is no national, high-resolution map of where current WUI areas are located or estimates of how much area the WUI covers. Many studies, primarily done in the United States, have not only mapped the current area of WUI up to a national scale (Menakis *et al.* 2000; Radeloff *et al.* 2005; Caballero *et al.* 2007; Theobald and Romme 2007; Haas *et al.* 2013; Tully 2013; Chuvieco *et al.* 2014; Thomas and Butry 2014), but have also mapped past changes in WUI (Hammer *et al.* 2007; Theobald and Romme 2007; Zhang *et al.* 2008; Tully 2013; Bouillon *et al.* 2014; Fox *et al.* 2015) and predicted future WUI changes (Theobald and Romme 2007).

Lack of Canadian WUI mapping is not due to a shortage of interest or importance. In a 2005 report compiled by the Canadian Council of Forest Ministers which aimed to assess future wildland fire strategic directions in Canada, WUI mapping was identified as a critical priority for fire research (Canadian Council of Forest Ministers 2005). However, WUI research in Canada is

particularly challenging due to lack of appropriate input data. To map the WUI, data on both structures and on wildland fuels are required. Various national fuels or land cover maps are available, but until recently, there was no national database of structure locations that was at an appropriate scale to map WUI areas. Census block housing density data or coarse-scale global population datasets were available, but using that type of data has limitations, and particularly in Canada, would result in inaccurate maps (see section 2.1 for more discussion on this topic).

WUI mapping may also be lacking because it is a large and complex issue. WUI fires are the result of a complex interaction involving structures, fire ignitions, fuels, weather, topography, and people (Hammer *et al.* 2007; Rehm and Mell 2009; Parisien *et al.* 2016) with multiple spatial and temporal scales at play simultaneously (Rehm and Mell 2009; Herrero-Corral *et al.* 2012). Individual elements are not understood well enough independently and require much more research before they can be incorporated into WUI models. For example, fire behaviour alone, and particularly fire behaviour in the WUI has many questions left unanswered. Firebrand production, transport, and ignition are not well understood (Hammer *et al.* 2007; Manzello *et al.* 2008; Mell *et al.* 2010; Maranghides and Mell 2011; Maranghides and Mell 2012) and neither is fire spread in the WUI with complexities such as home-to-home ignitions and interactions between wildland and structure fires (Rehm and Mell 2009; Mell *et al.* 2010; Maranghides and Mell 2011; Caton *et al.* 2016). Additionally, when studying the WUI, suppression and mitigation activities must be accounted for since they can have a dramatic effect on fire activity and on whether structures survive a wildland fire (Mell *et al.* 2010; Maranghides and Mell 2011; Calkin *et al.* 2014; Parisien *et al.* 2016).

1.3   Defining the "WUI"

In order to map the WUI, quantitative definitions of what makes a home or an area "WUI" must be defined. Defining the WUI in qualitative, general terms is easy to do on the ground, in person on a house-by-house basis, but is much more challenging on a larger scale in a quantitative way. The WUI can take a variety of forms, with varying housing densities and arrangements interacting with different wildland fuel types, loads, structures and so on (as discussed in Lein and Stump (2009)). For this reason, defining the WUI is a challenge, and has resulted in inconsistent definitions throughout the scientific literature (Mell *et al.* 2010; Maranghides and Mell 2012).

The term "WUI" did not always refer to wildland fires and structures; the term has evolved over time. Bradley (1984) discussed it in reference to differing needs between forestry and urban areas, and Davis (1990) applied a general definition of what constitutes WUI in the context of fire. From there, more research on fire issues in the WUI was performed, leading Stewart *et al.* (2007) to state: "[t]he term "wildland–urban interface" is now used almost exclusively in the context of wildland fire." The most frequently cited general definition of WUI comes from a 2001 US report (USDA and USDI 2001) and describes the WUI as "…where humans and their development meet or intermix with wildland fuel." That report goes into further detail, describing the types of WUI (e.g. intermix vs interface) and outlining risk[2] factors in the WUI. Out of necessity, studies that aimed to map the WUI have created their own quantitative definitions. These definitions vary and are generally based on one or more of the following: local conditions or characteristics of the WUI, data availability, the intended use of the information, and any definitions or guidelines from policy or laws within the study area (as discussed in Wilmer and Aplet (2005), Stewart *et al.* (2009), Platt (2010), Bar-Massada *et al.* (2014), and Modugno *et al.* (2016)). Due to variation in even minor details of the specific WUI definitions, studies performed in the same areas, with the same data sources, and the same general definitions may end up with differing results (Theobald and Romme 2007; Stewart *et al.* 2009; Bar-Massada *et al.* 2013; Bouillon *et al.* 2014). These differing approaches, results, and map uses are certainly complex (as is the WUI itself), but this is not necessarily a problem. As Stewart *et al.* (2009) put it, "[t]he solution is not to declare a single map best or, conversely, to tell managers not to use a given map because it is wrong, but rather to consider the purpose for which each map was developed and critically evaluate the quality of the data and analysis on which it is based." It should be noted that using appropriate definitions of what constitutes the WUI and keeping them consistent over a study area or over time periods is necessary for

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[2] *It should be noted that the term "risk" is defined in various ways in the literature, but in the context of this study, WUI does not directly include risk (following the true definitions and applications of both WUI and risk). Risk is defined as the product of fire danger (which includes fire ignition and fire spread) and vulnerability to fire (including potential losses)(Chuvieco et al. 2014). The pure presence of structures and flammable wildland fuels designates an area as WUI, and is independent from risk (Radeloff et al. 2005; Zhang et al. 2008; Haas et al. 2013; Tomas and Butry 2014). However, if a modular approach (as suggested/used in Hammer et al. (2007), Radeloff et al. (2005), and Lein and Stump (2009)) is taken where the WUI area is combined with other factors reflecting the probability of fire ignition and spread to a structure, the probability of structure loss, and the value of potential losses (Fried et al. 1999; Chuvieco et al. 2014), it is possible to produce a more complete picture of risk.*

comparing results or investigating changes in an area (McFarlane 2006; Platt 2010; Chas-Amil *et al.* 2013). Table 1-1 displays a summary of the varying definitions of WUI in mapping studies in the literature, along with details of location, spatial resolution, scale, and input data sources for each study. In these studies, there are typically three components that require strict definitions or thresholds: WUI structures, flammable wildland fuels, and some buffer distance where the intersection of the fuels and structures are relevant.

To summarize the variety of methods in Table 1-1, there are four general approaches to defining and mapping the WUI. For discussion purposes here, these four approaches discussed in the following sections are referred to as the: "*zonal approach*", "*category approach*", "*structure-based approach*", and "*fire occurrence approach*". Each approach has strengths and weaknesses, which will be discussed in the following sections. As mentioned previously, the choice of what approach to take is generally based on: local conditions or characteristics of the WUI, data availability, the intended use of the information (including spatial scale), and any definitions or guidelines from policy or laws within the study area (Wilmer and Aplet 2005; Stewart *et al.* 2009; Platt 2010; Bar-Massada *et al.* 2014; Modugno *et al.* 2016).

Some studies included in Table 1-1 did not explicitly map the WUI (Menakis *et al.* 2000; Alexandre *et al.* 2014; McGee *et al.* 2014) or are not limited to only mapping the WUI and add in burn probability or other elements of fire risk (Haight *et al.* 2004; Lowell *et al.* 2009; Haas *et al.* 2013; Whitman *et al.* 2013; Chuvieco *et al.* 2014; Price and Bradstock 2014; Fox *et al.* 2015). These publications were included in the list of studies to demonstrate the variety of definitions.

1.3.1 Zonal Approach

The first approach that will be discussed here is the "*zonal approach*". This approach is the most common and uses strict thresholds of housing density and vegetation cover and is based on census blocks (i.e. areas of varying sizes and shapes over which national census data is aggregated). Stewart *et al.* (2003) (and subsequent publications: Radeloff *et al.* (2005) and Stewart *et al.* (2007)) pioneered this method. They relied on the original USDA and USDI (2001) policy definition of the WUI and required a minimum number of housing units in a census block area (equivalent to > 1 housing unit per 16 ha) and a minimum vegetation cover requirement (> 50%; but < 50% was included if within 2400 m of a > 500 hectare densely

Table 1-1. Definitions and methods used in interface mapping studies.

Interface mapping definitions and basic information of previous interface mapping studies including: publication, location of map, resolution, scale (continental, national, regional, provincial/state, district, county, department, local, community), input data for human (structures/population) and vegetation, and definitions of what constitutes an interface "structure", what "wildland fuels" are, and the "buffer" distance (if used). Not available stated as N/A.

Publication	Location	Resolution	Scale	Input Data		Definitions		Buffer
				Human	*Vegetation*	*Structure*	*Wildland Fuels*	
Menakis *et al.* (2000)	USA (conterminous)	1 km	National	LandScan Global Population 1998, US Census 2000 (housing)	Potential Natural Vegetation Groups version 2.0, Current Cover Types Layer version 1.0	Housing density (houses/ha) categories.	Burnable cover types (e.g. coniferous, dense shrub, deciduous, grassland, savanna, sparse shrublands); categories reflected the "maximum fire intensity that could occur in these vegetation types under extreme weather conditions".	2000 m
Stewart *et al.* (2003); Radeloff *et al.* (2005); Stewart *et al.* (2007)	USA (conterminous)	30 m	National	US Census 2000 (housing)	NLCD 1992	Census block with > 1 housing unit per 16 ha. Stewart *et al.* (2007) used dasymetric mapping of housing (removed public lands).	Burnable cover types (coniferous, deciduous, mixed forest, shrubland, grassland, herbaceous, transitional, woody and emergent herbaceous wetlands) covering >50% of the area in a census block. Vegetation covering <50% could be included if within 2400 m of a large (>500 ha) densely vegetated (>75%) area.	2400 m
Haight *et al.* (2004)	Northern lower Michigan, USA	30 m	County	US Census 2000 (housing)	1994 classified LandSat image	Census block with > 1 housing unit per 16 ha.	Wildland fuels (forest, shrubland, grassland) covering >50% of the area in a census block. Vegetation covering <50% could be included if within 2400 m of a large (>500ha) densely vegetated (>75% coverage) area.	2400 m
Wilmer and Aplet (2005)	3 states in USA	30 m	State	US Census 2002 (housing)	NLCD 1992	Census block with >= 1 housing unit per 16 ha. Dasymetric mapping of housing (public lands removed).	Wildland fuels (forests, shrubland, grasslands, herbaceous wetlands).	800 m

Publication	Location	Resolution	Scale	Input Data		Definitions		
				Human	*Vegetation*	*Structure*	*Wildland Fuels*	*Buffer*
Caballero *et al.* (2007)	Spain	250 m	National	Spain settlement map (2000), CORINE Land Cover urban areas, night light satellite image, EUROSTAT	CORINE land cover (2000), Spanish Forestry Map	Each community was subjectively classified into categories based on housing density and arrangement: isolated house, dispersed housing area, dense uniform intermix, intermix, interface with a compact settlement, interface with rural town, interface with large urban area, interface with industrial etc.	Wildland fuels (dense forest, agroforest, shrub).	N/A
Hammer *et al.* (2007)	3 states in USA	30 m	State	US Census	NLCD 1992	Census block with >= 1 housing unit per ~1 to 16 ha.	Burnable cover types (forest, shrubland, grassland) covering >50% of the area in a census block. Vegetation covering <50% could be included if within 2400 m of a large (>500 ha) densely vegetated (>75%) area.	2400 m
Theobald and Romme (2007)	USA (conterminous)	30 m	National	US Census	NLCD 1992 (fuel location) and FUELMAN 2002 (forest types)	Census block with >= 1 housing unit per 16 ha with dasymetric mapping of housing (based on protected land, public lands, water, major roads).	Wildland fuels (forested, shrubland, grassland (but not tundra), and wetlands).	Variable-width buffer categories based on vegetation type (maximum distances of 800, 1600, and 3200 m).
Zhang *et al.* (2008)	Southeastern USA	30 m	Regional	US Census (1990, 2000)	NLCD (1992, 2001)	Census block with >= 1 housing unit per 16 ha.	Wildland fuels (forested cover types, shrublands, grassland/herbaceous, transition, woody and emergent herbaceous wetlands) with >= 60% density.	2400 m
Lowell *et al.* (2009)	3 areas in Victoria, AUS	~35 cm	Local	Classification of digital orthophotograph	Classification of digital orthophotograph	Any structure that was within fire scar of three past fires.	Rank of forest density from orthophotograph classification (dense to medium forest, scattered forest to grassland-non forest).	N/A

Publication	Location	Resolution	Scale	Input Data		Definitions		
				Human	*Vegetation*	*Structure*	*Wildland Fuels*	*Buffer*
Beverly *et al.* (2010)	4 communities in Alberta, Canada	5 m	Community	Supervised classification (with use of property lines, municipal information, local knowledge, field visits) of 1 m aerial photos	Supervised classification of 1 m aerial photos	All primary structures (not outbuildings or detached garages), but also included were lawns, streets, parking lots, managed vegetation (i.e. parks), outdoor recreation infrastructure, and electrical and communications infrastructure.	Fire Behavior Prediction (FBP) fuel types C1, C2, C3, C4, C7, M2, and in some cases O1 (left out deciduous, water, and non-fuel such as non structural industrial facilities, bare rock/soil, wetlands, marshes, beaches, seismic lines, roads, managed grasslands (i.e. agriculture, playing fields, airport strips).	30 m / 100 m/ 500 m depending on ignition process under consideration (radiation, short-range spotting, or long-range spotting).
Lampin-Maillet *et al.* (2010)	SE France	2.5 m	Department (one level below region in France)	French National Geographical Institute housing data and Spot 5 satellite image (2002)	Supervised classification of Spot 5 satellite image (2002)	All homes < 200 m of wildland vegetation in categories based on housing densities: isolated, scattered, dense clustered, and very dense clustered.	Wildland fuels (forests, scrublands, transitional lands) in categories of vegetation aggregation: no vegetation, sparse vegetation, continuous vegetation.	100 m fixed buffer.
Platt (2010)	4 counties across USA	30 m	County	County parcel data	Landfire 2006 (tree heights), and NLCD (land cover)	Structures mapped by parcel centroid; removed if "remote" (i.e. 569 m from another structure).	"Non-wildland" vegetation removed from buffered WUI area.	800 m or 0-595 m depending on tree height.
Galiana-Martina *et al.* (2011)	1 region in Spain	25 ha / 2.5 m	Regional to municipal	Orthophotograph	CORINE land cover 1987 and 2000 and a SPOT5 satellite image	Categories of settlement types (town/urbanizations/scattered rural settlements) and building density (m2/ha) categories: 0-300 (low), 300-1500 (medium), >1500 (high).	Categories of land cover types (western muelas, wildland mountain, agroforestal slopes, agricultural valleys, agricultural foothill plains) and vegetation aggregation index categories (zero (index = 0), medium (index 0-90), high (>90)).	100 m fixed buffer.
Herrero-Corral *et al.* (2012)	Western Madrid, Spain	Up to 0.5 m	Regional, local, community	Spanish Geographical Institute vector layer of structures	Spanish Forest Map, aerial photos	All homes < 400 m of wildland vegetation in categories based on housing densities: isolated, scattered, dense clustered, and very dense clustered.	Vegetation aggregation categories (no vegetation, sparse vegetation, continuous vegetation).	100 m fixed buffer.

| Publication | Location | Resolution | Scale | Input Data | | Definitions | | |
				Human	*Vegetation*	*Structure*	*Wildland Fuels*	*Buffer*
Rozmajzl (2012)	4 US National Parks in 3 different central States	30 m, others not stated	Local	US Census 2010 or state-level structure point datasets	NLCD, LANDFIRE, or USGS Vegetation Characterization	Census blocks with >= 1 housing unit per 16 ha. Alternatively, structure point locations were used in some areas.	Burnable cover types (all were included except for sparse vegetation, developed land, water, cropland, barren, rock outcrops, floodplain, wetlands).	2400 m (around both point data and around census blocks).
Bar-Massada *et al.* (2013)	4 US locations spread across the country	30 m	Local	US Census method 1. Method 2 used USDA/USGS point structure data or digitized structure locations from Landsat images	NLCD	Census blocks (method 1) or pixel with moving window value (method 2) that has > 1 housing unit per 16 ha.	Wildland fuels.	2400 m (method 1), 100-1000 m (method 2).
Chas-Amil *et al.* (2013)	Galicia (NW Spain)	25 m	Region	Spanish National Topographic Base (2006) and Cartographic Numeric Base	Land Cover and Use Information System of Spain and aerial photos	All homes < 400 m of wildland vegetation in categories based on housing densities: isolated, scattered, dense clustered, and very dense clustered.	Wildland fuels (forests, scrublands, transitional lands) in categories of vegetation aggregation: no vegetation, sparse vegetation, continuous vegetation.	50 m around structures and 400 m around fuels.
Gowman (2013)	Ontario, Canada	25 m	Province	Land Information Ontario database	Provincial Fuels Database (Landsat imagery and Forest Resource Inventory data), GlobCover Land Cover	All houses (points) were buffered.	Wildland fuel (fuel types, plus sparse vegetation and non-irrigated crops).	Variable-width buffer based on fuel type out to a maximum of 2400 m; non-fuel areas removed from buffer.
Haas *et al.* (2013)	USA (conterminous)	90 m	National	LandScan USA (dasymetric mapping of census data) 2009 population	LandScan 2009	Population density categories (people per 7.29 ha: low 0.01–0.8 people, medium 0.8–7.0 (Intermix), high >7.0 people (Interface)).	Wildland fuels (omitted water, snow/ice, urban, agricultural, barren).	N/A

Publication	Location	Resolution	Scale	Input Data		Definitions		
				Human	*Vegetation*	*Structure*	*Wildland Fuels*	*Buffer*
Tully (2013)	USA (conterminous)	30 m	National	US 2010 Census data, with additional data for dasymetric methods removing areas of public lands, water, and low road density	LANDFIRE	Census block with >= 1 housing unit per 16 ha after dasymetric mapping removed areas of public lands, water, and low road density.	Variable-width buffer based on vegetation type (sparse, herb, shrub, forest) and height.	Variable-width buffer based on vegetation type and height is a maximum of 480 m; buffer around census blocks was 510 m.
Whitman *et al.* (2013)	Halifax Regional Municipality, Nova Scotia, Canada	Not stated	Municipal	Building footprints and municipal lot centroids	Nova Scotia Department of Natural Resources Forest Fuel Code, LiDAR fuel height data, QuickBird satellite imagery	All structures in the study areas.	Refined forest fuel code types (forest, slash, matted grass).	N/A; only areas within community boundaries considered.
Alexandre *et al.* (2014)	USA (conterminous)	30 m	National	Manual classification of Google Earth imagery	N/A	All buildings within burn perimeters.	N/A	N/A
Bouillon *et al.* (2014)	Various (Europe)	Unstated for methods 1 and 2; method 3: 100 m	Multiscale: methods 1 and 2 were local, method 3 was "global" (European)	Not stated/various	Not stated/various	Method 1) Any structure < 200 m from wildland fuels classified into categories based on housing densities (isolated, scattered, dense clustered, and very dense clustered). Method 2) Any structure < 400 m from wildland fuels into categories based on housing density/arrangement. Method 3) Any structure < 200 m from wildland fuels into categories (isolated, scattered, dense cluster).	Method 1) Three categories of wildland fuels (forest or scrubland) based on vegetation densities: no vegetation, sparse vegetation, continuous vegetation, by categories of vegetation aggregation: no vegetation, sparse vegetation, continuous vegetation. Method 2) Categories based on type (forest, agricultural) and % coverage. Method 3) Categories based on type: mineral, agriculture, sparse vegetation and forest.	1) 100 m 2) variable from 100-400 based on structure and fuel categories. 3) 400 m

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Publication	Location	Resolution	Scale	Input Data		Definitions		
				Human	*Vegetation*	*Structure*	*Wildland Fuels*	*Buffer*
Chuvieco *et al.* (2014)	Spain	100 m	National	CORINE Land Cover map	CORINE Land Cover map	All structures within 100 m of wildland fuels.	Wildland fuels (trees, shrubland).	100 m
McGee *et al.* (2014)	Canada	N/A	National	Census 2011	Rowe's 1972 Forest Regions of Canada	Populated places (census block centroids) of a community.	Forested areas with >= 20% cover (coarse scale forest regions).	2400 m
Price and Bradstock (2014)	Sydney region, Australia	100 m	Region	New South Wales Digital Cadastral Database (2007)	Native vegetation map of New South Wales	Any urban area with > 2 properties/ha.	N/A	500 m
Taylor *et al.* (2014)	Canada	30 m / N/A	National	Census	GeoBase Landcover	All census blocks which intersect buffer area.	Burnable land cover types of at least 400 ha in size.	2000 m
Thomas and Butry (2014)	USA (conterminous)	1 km	National	Census	NLCD	Census blocks with >= 1 housing unit per 16 ha.	Burnable cover types (forest, shrubland, grassland) covering >50% of the area in a census block. Vegetation covering <50% could be included if within 2400 m of a large (>500 ha) densely vegetated (>75%) area.	2400 m
Fox *et al.* (2015)	2 small areas in SE France	5 m	Department (one level below region in France)	BD TOPO (2009)	NDVI derived from 2009 aerial photos	Housing density by categories (isolated, scattered, dense clustered, and very dense clustered).	NDVI vegetation mapping density by categories (sparse vegetation (NDVI < 0.01), discontinuous (0.01- <0.15), continuous vegetation (>0.15)).	100 m fixed buffer.
Modugno *et al.* (2016)	Europe	100 m	Continental	CORINE Land Cover map (2006)	CORINE Land Cover map (2006)	All "artificial areas" from the land cover map. Included urban areas, but also dump sites, industrial or commercial units, construction sites, and sport and leisure facilities.	Fuels from the land cover map (forest, sclerophyllous vegetation, and transitional woodland-shrub).	200 m around artificial areas; 400 m around fuels. WUI is the intersection of these buffers.

vegetated (i.e. > 75% cover) area). Since this method is founded upon the general WUI definition developed in the United States, the zonal method is primarily used within the United States. The benefits of using this approach include 1) the method follows the existing policy guidelines and 2) that this approach permits the use of what is usually the best available data (census data). However, these same benefits also result in weaknesses since 1) following policy guidelines result in subjective thresholds in the definition (e.g. the > 1 housing unit per 16 ha) and 2) the use of census data is not the ideal data for mapping at the scale of the interface (e.g. see section 2.1 for a discussion on the use of census data).

Enhancing the Stewart *et al.* (2003) zonal method, Wilmer and Aplet (2005) added "dasymetric mapping" to address some of the limitations of using census data. Dasymetric mapping is a method that uses one or more additional data sources to interpolate or refine the spatial distribution of census housing density information or other similarly spatially aggregated data (Mennis 2003). In the case of the Wilmer and Aplet (2005) study, land where there are likely no structures (i.e. public lands) are removed from the area under consideration for WUI mapping, thus improving the accuracy of the spatial location of the WUI and reducing the incidence that a census block would be entirely left off the map because it did not meet the minimum housing criteria (> 1 housing unit per 16 ha).

Theobald and Romme (2007) and Haas *et al.* (2013) continued and extended the use of dasymetric mapping. Theobald and Romme (2007) removed areas that are unlikely to contain homes (i.e. protected land, public land, water) and also distributed housing density according to where the homes are more likely to be located (i.e. weighted by density of major roads). Haas *et al.* (2013) took advantage of a dataset called "LandScan" which employs extensive dasymetric mapping of census information to estimate population location in the United States.

An additional enhancement to the existing zonal approach methods was done by Theobald and Romme (2007). Instead of a static buffer distance (known as "isotrophic buffering") as had been used previously, a variable-width buffer was used to reflect the variation in vegetation type surrounding the modified census housing area. The actual buffer distance around each housing area varied, depending on a subjective ranking of the difficulty of mitigating fire in the surrounding vegetation (e.g. fire in coniferous forest is more difficult to mitigate than in a deciduous forest or wetland area, and these differences are reflected in the ranking of these fuels). The variable-width buffer radiated from the housing areas out to a

maximum distance[3] of 3200 m, based on the fuel rankings (e.g. the maximum buffer distance would be expressed in an area with a pure conifer fuel, and a much smaller buffer would be seen in an area surrounded by deciduous forests or wetlands). The inclusion of this variable-width buffer resulted in a much more accurate estimation of the area of WUI as it reflects the fuel conditions and actual WUI area more accurately (see section 2.2.3 for more discussion on variable-width buffering). Tully (2013) also made use of this type of variable-width buffering, but distances were based on vegetation type and height, and their corresponding maximum potential flame height and appropriate firefighter safety zones (Butler and Cohen 1998) to approximate a structure ignition zone.

The definitions and zonal methods developed in Stewart *et al.* (2003) (and subsequent publications: Radeloff *et al.* (2005) and Stewart *et al.* (2007)) were also used in several other studies, some with minor modifications or additions (see Haight *et al.* (2004), Hammer *et al.* (2007), Zhang *et al.* (2008), Rozmajzl (2012), Bar-Massada *et al.* (2013), Taylor *et al.* (2014), and Thomas and Butry (2014)). Wigtil *et al.* (2016) also used the WUI maps produced in Radeloff *et al.* (2005) to produce maps of what they refer to as "place vulnerability", by combining the WUI map with wildfire potential and social aspects of census data (reflecting social conditions that may make an area vulnerable to damage by wildfire).

1.3.2 Category Approach

The second approach to defining the WUI (known here as the "*category approach*") crosses categories of structure location data with categories of vegetation data to produce a variety of WUI categories. There is some variety in the specific methodologies using this approach, but the methods from Lampin-Maillet *et al.* (2010) are the most frequently used. Lampin-Maillet *et al.* (2010) took actual structure locations (i.e. not zonal census data) and classified structure density into four categories (isolated, scattered, dense clustered, and very dense clustered) based on the surrounding structure arrangement. Three vegetation categories were also created for the same areas, defined by presence of burnable vegetation and its aggregation (no vegetation, sparse vegetation, continuous vegetation). The 4 housing categories were then crossed with the 3 vegetation categories, producing 12 WUI categories (e.g. an area could be classified as isolated housing and sparse vegetation) which are customized to the

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[3] *In addition to 3200 m, maximums of 1600 m and 800 m were also investigated for application to different fire mitigation activities.*

conditions of the study area in France. These categories were only applied in a fixed-width buffer of 100 m from every structure, following the application to policy within the study area[4]. This method does provide an additional level of detail compared to other WUI mapping methods, in that the density of both the fuel and structures are provided (from the categories). However, these categories only apply within the study area and are based on the local conditions.

There are several studies using the category approach and variations on the Lampin-Maillet *et al.* (2010) method; all performed in France or Spain. Variations on the existing method include minor changes (Chas-Amil *et al.* 2013; Bouillon *et al.* 2014; Fox *et al.* 2015) or modification of the 12 categories, incorporating fire vulnerability (Galiana-Martina *et al.* 2011) or landscape characteristics such as topography (Herrero-Corral *et al.* 2012).

Caballero *et al.* (2007) developed an alternative method within the category approach of defining the WUI. However, this method is a subjective, visual categorization of housing density, housing arrangement, and fuels and thus is of limited use for quantitatively defining the WUI.

Two additional (but unpublished) methods of defining the WUI are briefly (and incompletely) discussed in Bouillon *et al.* (2014). Both methods are based on the Lampin-Maillet *et al.* (2010) technique, but use slightly different structure categories and/or add on additional vegetation information.

1.3.3   *Structure-Based Approach*

The third approach to defining the WUI, the "*structure-based approach*", is the approach used in this study, as will be discussed in chapter 2. This approach uses actual structure locations, as opposed to aggregated data as in the "*zonal approach*". Though both the structure-based approach and the category approach use structure locations, this approach does not attempt to categorize the WUI into a matrix of WUI types. The use of the actual structure locations in this method produces a spatially explicit delineation of WUI areas. The structure-based approach is generally much more labour-intensive due to the fine scale required; structure location data on a large scale are surprisingly scarce in many areas and require significant processing to produce and process (Cleve *et al.* 2008; Bar-Massada *et al.* 2013). Alternatively, the lack of structure location data can be circumvented by using the best available data (e.g. land parcel data as in

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[4] *In France, the location of the Lampin-Maillet et al. (2010) study, there is a law which makes it mandatory for home owners to clear wildland fuels in a radius 100 m from their structures if it is located less than 200 m from fuels (Lampin-Maillet et al. 2010).*

Platt (2010) or census data as discussed in the zonal approach WUI mapping methods). However, using parcel data to approximate housing locations is inaccurate due to the assumption that the structure is located in the centre of the parcel (Platt 2010; Bar-Massada *et al.* 2013). The zonal approach is even more inaccurate due to what is termed the "modifiable areal unit problem", which occurs when point data are aggregated into areas with boundaries that are arbitrary, or "modifiable" (such as census block boundaries) (Openshaw 1984; Bar-Massada *et al.* 2013) (see section 2.1 for more discussion on this topic).

Both Rozmajzl (2012) and Bar-Massada *et al.* (2013) used and compared the structure-based approach and the zonal approach methods within their study areas in the United States. Rozmajzl (2012) took advantage of existing local structure point locations in three of their four study areas. National vegetation data was intersected with the structure locations, and the WUI was identified as the buffer area (2400 m) around every individual structure. Compared to using census data in the same study areas, WUI area either increased or had no change (depending on location) when using the actual structure locations. Bar-Massada *et al.* (2013) digitized structure locations from remotely sensed images of their study areas and used a moving window neighbourhood analysis to match the policy-based housing density definitions used in the traditional zonal approach; thus their structure-based approach is a hybrid between the structure and zonal approaches.

Beverly et al. (2010) employed supervised classification of aerial photographs for four communities in Alberta, Canada to delineate structure locations and burnable fuel types in order to map WUI areas on a fine scale (5 m resolution). Only primary structures were considered (removing outbuildings and detached garages), but elements of what is referred to as the "built environment" are included (areas next to a primary structure which included lawns, streets, parking lots, electrical and communications infrastructure, and parks). Three buffer distances around areas identified as structures or other components of the "built environment": 30 m for radiative heat, 100 m for short-range spotting, and 500 m for long-distance spotting. The resultant WUI maps were a composite of the exposure to each ignition processes individually, and all three ignition processes together.

Gowman (2013) took the structure-based approach in mapping the WUI, since structure location data was available in the study area (the province of Ontario, Canada). Vegetation data and structure locations were intersected, and the WUI was identified as the buffer area around every individual structure. The Gowman (2013) study added the use of a variable-width buffer,

which varied based on fuels surrounding the structure (similar to the methods in Theobald and Romme (2007)), out to a maximum distance of 2400 m in the fuel types with the potential for the most extreme fire behaviour. Additionally, "non-fuel" (e.g. water, barren land) areas were removed from the buffer areas, forming a more accurate area estimate of the WUI.

The structure-based approach was also used in Whitman *et al.* (2013) with building footprint or lot centroids available for their two study areas (both in the municipality of Halifax, Nova Scotia, Canada). All structures within the community boundaries of the study area were considered WUI structures, and the WUI within those community boundaries was mapped based on the surrounding fuels with a modelled burn probability over a designated threshold.

Chuvieco et al. (2014) used the structure-based approach to mapping the WUI in Spain, which was incorporated into their fire risk study. Unlike other studies, WUI was defined as structure monetary value found within a 100 m distance from wildland fuels.

The most recent study using the structure-based approach is Modugno *et al.* (2016) which was performed in Europe. Data on both fuels and "artificial areas" were obtained from coarse resolution land cover data. Similar to many of the previous studies, artificial areas were buffered (200 m), but unlike the majority of studies using buffering, fuels were also buffered (400 m). The WUI area was defined as the areas these two buffers overlap; non-fuel areas were not removed from the final WUI areas.

1.3.4   *Fire Occurrence Approach*

The fourth general approach to defining and mapping the WUI defined here is referred to here as the "*fire occurrence approach*". This method relies on the use of past wildfire data to define WUI areas and has only been used in Australia. Houses located within burned areas of wildfires are simply deemed to be WUI structures, making this a straightforward method which also adds one element of fire risk (i.e. fire occurrence). However, this method is only useful in areas with high fire occurrence, with reliable fire data, and it makes the assumption that past fire occurrence will be similar to future. Lowell *et al.* (2009) uses this method for three fire scar areas (plus 500 m of bordering area to account for errors in fire mapping). Somewhat similarly, Price and Bradstock (2014) defined the WUI as simply any urban area with > 2 properties per hectare, with no regard to fuels in defining the WUI; but this definition is justified by the high fire occurrence in their small study area.

Though not explicitly mapping the WUI, Alexandre *et al.* (2014) manually classified individual structures located within past fire perimeters in the conterminous United States. Each house located within a burn perimeter was considered to be a WUI structure. Fuels were not considered and WUI area was not calculated.

1.4   Previous Interface Mapping Efforts

In this section, details beyond the WUI definition criteria will be discussed, including spatial coverage, scale, and final products. Reviewing the existing WUI maps available, surprisingly few areas of the fire-affected world (Mouillot and Field 2005; FAO 2007; Bowman *et al.* 2009) have been studied. In the 29 studies included in Table 1-1, 14 focus on the United States, 5 on Spain, 5 on Canada, 2 on Australia, and 2 on France. There is also a single study (Modugno *et al.* 2016) which looked at (the majority of) Europe, and another study (Bouillon *et al.* 2014) which looked at three study areas within Europe. No studies on mapping the WUI appear to have been published for Mexico, Central and South America, Africa, and Asia.

Of the current WUI studies in the literature, the majority of maps were produced at the national scale, but also with many done at a regional, provincial/state, and local scale (listed in Table 1-1). Several were done at a scale between local and regional (i.e. district/county/department), and a single study was done at a continental scale (Modugno *et al.* 2016). Often the decision of which scale to focus on is based solely on data availability or processing limitations, but the scale may also be chosen based on the intended purpose of the map. In order to quantify how the chosen scale affects the results or meaning of the mapped WUI areas, some studies have investigated the WUI at multiple scales. Both Galiana-Martina *et al.* (2011) and Herrero-Corral *et al.* (2012) discuss scale effects and suggest that the WUI should be defined and mapped based on data from regional to local/sub-local scales in order to accommodate the multiscale nature of the WUI problem.

WUI maps produced in the studies shown in Table 1-1 are generally available in the original publications for demonstrative purposes, but few mention data distribution for practical uses or further research. One notable exception comes from a continuation of the Radeloff *et al.* (2005) publication where an updated version of the national United States map was produced by Martinuzzi *et al.* (2015). This publication was intended for distribution online or in print and it maps the WUI for every conterminous state in the United States. In France, though the WUI maps themselves are not available, the Lampin-Maillet *et al.* (2010) methods of calculating the

WUI are available as computer software (Lampin-Maillet and Bouillon 2011). This software has also been modified to suit WUI mapping in Spain (Herrero-Corral *et al.* 2012).

1.5   Industrial and Infrastructure Interface

Interface research has focused almost exclusively on the urban aspect (thus the "WUI"). The WUI does also include, in some cases, rural areas and areas with more dispersed housing arrangements (e.g. cottage areas), but these situations are lumped together with the "urban" interface. However, three studies did include more than just the traditional "urban" structures in their "WUI" mapping. In Spain, Caballero *et al.* (2007) included industrial structures, Modugno *et al.* (2016) included "industrial or commercial units" in their European map, and Beverly *et al.* (2010) included electrical and communications infrastructure in their maps of four Alberta communities. In all three cases, these industrial or infrastructure areas were grouped together with the residential structures to form the WUI map. The focus on the "urban" aspect is logical; people's homes, community buildings, and businesses are the structures that firefighters are most obligated to protect from fire. Though people work within industrial areas, and industrial structures have been destroyed by wildfire or are at risk from wildfire (Beverly and Bothwell 2011; Thomas and Butry 2014), these areas are not prioritized over a community. While communities rank higher than industry when considering which areas to protect, it is important to consider that damages to, or the loss of, industrial areas can result in monetary losses from production shutdowns when wildfires occur. These shutdowns can be caused by evacuations of workers (due to direct threat of wildfire, evacuation route cut-off, or smoke), service shutdowns (in the case of power transmission or gas lines), or destruction of crucial equipment or structures. For example, wildfires in Northern Alberta in 2011 caused shutdowns of oil and gas extraction areas and pipelines, quickly resulting in millions of dollars in losses to the industry and contributed to a 0.1% decrease in Canada's national gross domestic product in that financial quarter (Statistics Canada 2011; Flat Top Complex Wildfire Review Committee 2012; McGee *et al.* 2014). Similarly, a 0.6% decrease in Canada's national gross domestic product in May 2016 was attributed to shutdowns during the 2016 Fort McMurray fire (CBC News 2016).

Industrial areas are a different type of interface with a different set of problems. For example, the risks of direct impacts from wildland fires to oil and gas facilities may be lowered due to having their own fire suppression systems and large areas of non-vegetated land buffering them from wildfires (Province of Alberta 1972; Province of Ontario 1990; Robinne *et al.* 2016).

Industrial areas are expanding, especially in Alberta with oil and gas extraction expansion (McGee *et al.* 2014; Canadian Council of Forest Ministers 2016), and the "wildland-industrial interface" (referred to here as the "WII") is emerging as an important, yet novel issue for interface mapping and will be included in this study.

A third "type" of interface could also be considered; this is referred to here as the "infrastructure interface". The infrastructure interface includes features such as roads, powerlines, and railways; these features aren't considered traditional "values" in that they are not necessarily structures, and furthermore they are not included in the traditional definition of the WUI. Despite this, these infrastructure components are important with regards to wildfire interface mapping for a variety of reasons. For example, infrastructure can be any of the following: an escape route for civilians during a wildfire (i.e. roads), values in need of fire protection (e.g. bridges, power and communication lines, pipelines), strategic firefighting features (e.g. burnout operations to a road), or sources of wildfire ignitions (e.g. railways). A map showing where these infrastructure features intersect or intermingle with wildland fuels would be valuable for research and practical applications, and will be included in this study.

The three interface types (WUI, WII, and infrastructure interface) are distinct and have varying applications; they should remain separate entities. However, considering the three interface types together may be beneficial to certain applications. The three types grouped together could be referred to as the "wildland-human interface" (as suggested in Robinne *et al.* (2016)), or more simply the "interface". Since there has been no previous work done on the spatial distribution of either the WII or the infrastructure interface anywhere in the world, this study will represent the first effort to map these areas.

1.6   Research Objective

In this study, the lack of national interface maps in Canada will be addressed. The primary research goal is to produce three national maps: one for the traditional wildland-urban interface (WUI), another for the wildland-industrial interface (WII), and a third for the infrastructure interface. To produce these maps, fuels, structures, and buffer areas which ultimately form the interface areas are defined and mapped at a national scale. These maps will represent the first national interface maps for Canada, and will be the first maps of the WII and industrial interface anywhere in the world.

From these maps, general information and statistics will be provided for the country and also by political and functional boundaries. Spatial patterns in the interface will be analysed. Additionally, the relationships between interface areas and fuels, structures, and past fires will be investigated. This work will provide a baseline for future research (e.g. risk mapping and prediction of future interface areas) but also has a variety of practical applications (e.g. fire management decision support and long-term planning, fire insurance, municipal planning, and fire mitigation).

2   INTERFACE MAP PRODUCTION

Three separate national maps (WUI, WII, and infrastructure interface) were produced in this study. Two national datasets were the input data, and a spatial structure-based approach (as discussed in section 1.3.3) was used to produce the outputs. Details on data availability, definitions of the interface and its components, and data processing are included in the following sections.

2.1   Data Availability

In order to map interface areas, data for human-built structures (i.e. homes, commercial buildings, industrial structures, infrastructure values) and wildland fuels are required. Data for structure locations in Canada was, until recently, not available at an appropriate scale for interface mapping. In this study, actual structure locations were used since the data is available from the CanVec+ (Natural Resources Canada 2015a) dataset produced by Natural Resources Canada on a national scale in a consistent format. Many global-scale population products are also available but generally the resolution is not high enough (e.g. 1 km resolution or higher) to effectively map the WUI, and thus these products were not used (e.g. Global Population of the World, Global Rural-Urban Mapping Project, LandScan Global Population Database, GlobCover, and CIESIN's Gridded Population of the World, Anthropogenic Biomes of the World, Global Human Footprint, and the Digital Chart of the World).

The availability of this data was the primary determinant as to which interface mapping approach to take (i.e. the structure-based approach, instead of the zonal approach, category approach, or fire occurrence approach; see sections 1.3.1 to 1.3.4). The category approach is not appropriate for this study due to the large scale and the need for a quantified method of classifying the interface. The fire occurrence approach would also not be suitable due to the large scale of the study, along with the reduced fire activity in Canada as compared to the areas of Australia (Mouillot and Field 2005; FAO 2007; Bowman *et al.* 2009) where the fire occurrence approach has been applied to calculate WUI area (Lowell *et al.* 2009; Price and Bradstock 2014). Finally, the zonal approach was not selected since actual structure locations were available, providing ideal data and eliminating need to rely on zonal data (the limitations of which are discussed further below).

Using actual structure locations circumvents many of the challenges and limitations of other WUI mapping studies (as discussed in Openshaw (1984); Cleve *et al.* (2008); Bar-Massada

et al. (2013)). In previous studies, lack of structure location data was dealt with typically in one of the following two ways: 1) mapping houses manually using classification of remotely sensed images (as in Cleve *et al.* (2008), Lowell *et al.* (2009), Bar-Massada *et al.* (2013), and Alexandre *et al.* (2014)), or 2) the use of broad-scale census housing density data, occasionally with dasymetric mapping (discussed in section 1.3.1) to refine structure locations (i.e. the zonal approach as used in Radeloff *et al.* (2005), Wilmer and Aplet (2005), Hammer *et al.* (2007), Theobald and Romme (2007), Bar-Massada *et al.* (2013), Haas *et al.* (2013), Tully (2013), and Thomas and Butry (2014)). With regards to the first method, classification of remotely-sensed data is extremely labour-intensive and not typically feasible at larger scales. The second method (using census data) is limited by the "modifiable areal unit problem" (as mentioned previously in section 1.3.3) presented by Openshaw (1984). This problem occurs when any sort of point-based data (e.g. structure locations) are aggregated spatially into areas (e.g. census blocks), resulting in a loss of precision and spatial accuracy, and are dependent on arbitrary boundaries (i.e. "modifiable" boundaries of census blocks).

Using structure data as opposed to census block data (where population counts are aggregated into census block areas, each of varying size and shape; i.e. the "zonal approach") is particularly beneficial within Canada. Canada's population mostly exists in large cities and is distributed along the southern border with the United States. There are also large areas of sparsely populated wildland areas which are generally areas with higher fire activity (Figure 1-1). The corresponding census block areas in Canada vary drastically between dense urban areas and sparsely populated areas. Dense urban areas have small census blocks; for example downtown Toronto, Ontario has an average of 2.6 hectare "Dissemination Blocks" (which are the smallest class of census blocks). Conversely, in sparsely populated northeastern Ontario, there is a census block that covers an area of over 12 million ha (roughly the size of England). As depicted in Figure 2-1a, when mapping the WUI using census blocks, the area may be overestimated if the entire census block is considered to be WUI when in fact there are clusters of structures and large areas of unpopulated land (as demonstrated in Taylor *et al.* (2014)). Alternatively, underestimation may occur; the subjective thresholds of structure density usually associated with WUI mapping using census data (i.e. > 1 housing unit per 16 ha) means that census blocks with low densities are not considered to be WUI areas. Figure 2-1b provides an example of underestimation of the WUI area that has sparse housing. Using census data to map WUI areas is also inaccurate due to the mismatch of spatial scale between the WUI mapping and

the census block size. For example, Figure 2-1a and Figure 2-1c have the same census area and housing density, but different spatial arrangement of structures. The WUI area would be deemed the same in these two areas using the census block zonal method, but in reality the two areas have very different WUI areas.
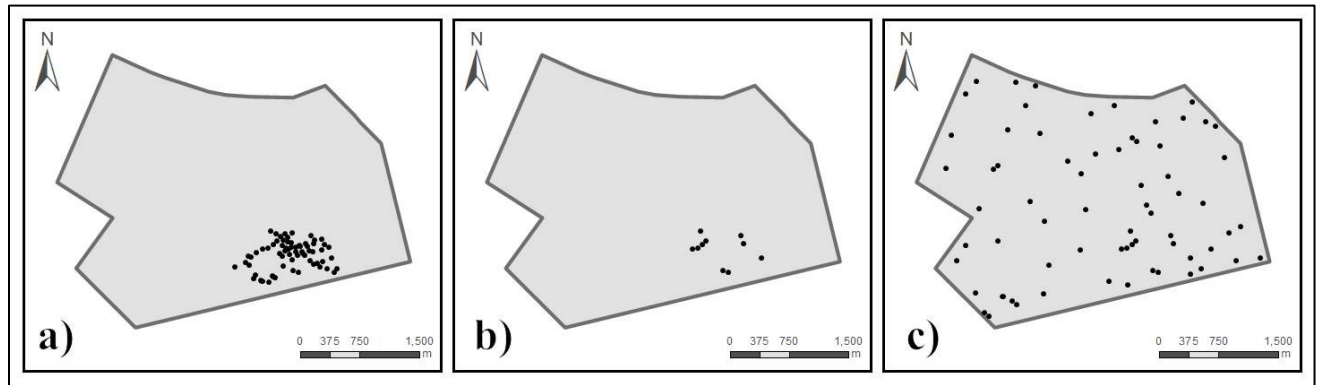
Figure 2-1. Map showing census blocks and structure locations.
Census dissemination blocks (the smallest census block size in Canada; boundaries from Statistics Canada (2015); shown in grey) with hypothetical structure point locations (black points). Image **a)** shows an example of overestimation of WUI area when using census blocks (large areas of unpopulated land is deemed WUI), image **b)** shows an example of underestimation of WUI area when using census blocks (housing density below threshold of 1 structure per 16 ha and is deemed not WUI), and image **c)** shows a census block with the same census area and housing density as the block shown in image a), but with a different spatial arrangement of structures; both images a) and c) would have the same amount of WUI area if a zonal approach using census blocks were used, but using a structure-based approach, the differing spatial patterns of housing arrangement would produce different WUI areas.

Data on burnable fuels were obtained from the Land Cover circa 2000 (Natural Resources Canada 2015b) dataset (LC2000), available through Natural Resources Canada. The LC2000 dataset is partially available within the CanVec+ dataset, with the forested categories of the LC2000 dataset forming the CanVec+ "Wooded Areas" layer. The original LC2000 dataset was used because mapping interface areas requires all wildland fuels to be considered, not just the forested areas. The LC2000 dataset is also available for 1996 and 2010; the "circa" 2000 version (data from 1996-2005, with the majority from 1999 to 2001) was selected for use since it includes data for above 60 degrees north latitude. The LC2000 dataset is based upon classified remotely sensed images from Landsat 5 and 7 and is compiled from three mapping initiatives (Land Cover for Agricultural regions of Canada, Northern Land Cover of Canada, and Earth Observation for Sustainable Development of Forests), with a 30 m resolution.

The vegetation cover types in LC2000 do not include detailed information on the fuels that are relevant to mapping WUI on a smaller scale (e.g. fuel structure and more detailed composition), but is among the best available for mapping on a national scale. LC2000 has the

appropriate spatial coverage (i.e. all of Canada) and resolution (30 m), and more comprehensive land cover classes than other land cover or fuel type maps (e.g. AVHRR Land Cover, Global Land Cover 2000, NSIDC's Global Land Use Datasets, National Forest Inventory, Nadeau Fuel Type Map, National Fuels Basemap, and GlobCover). Despite the fact that the data was collected "circa" 2000 and is thus out of date, this dataset still represented the best option for input to this study considering it contains the required fuel information for all of Canada at an appropriate resolution. Section 2.4 presents a discussion of the assumptions regarding the use of this dataset.

A sample image of the CanVec+ and LC2000 databases are shown in Figure 2-2 for Chapleau, Ontario and surrounding area. There are many features in the CanVec+ database that are not relevant to this study and thus not all available features are shown (structure selection is discussed in section 2.2.2). The vegetation land cover from LC2000 is also displayed.
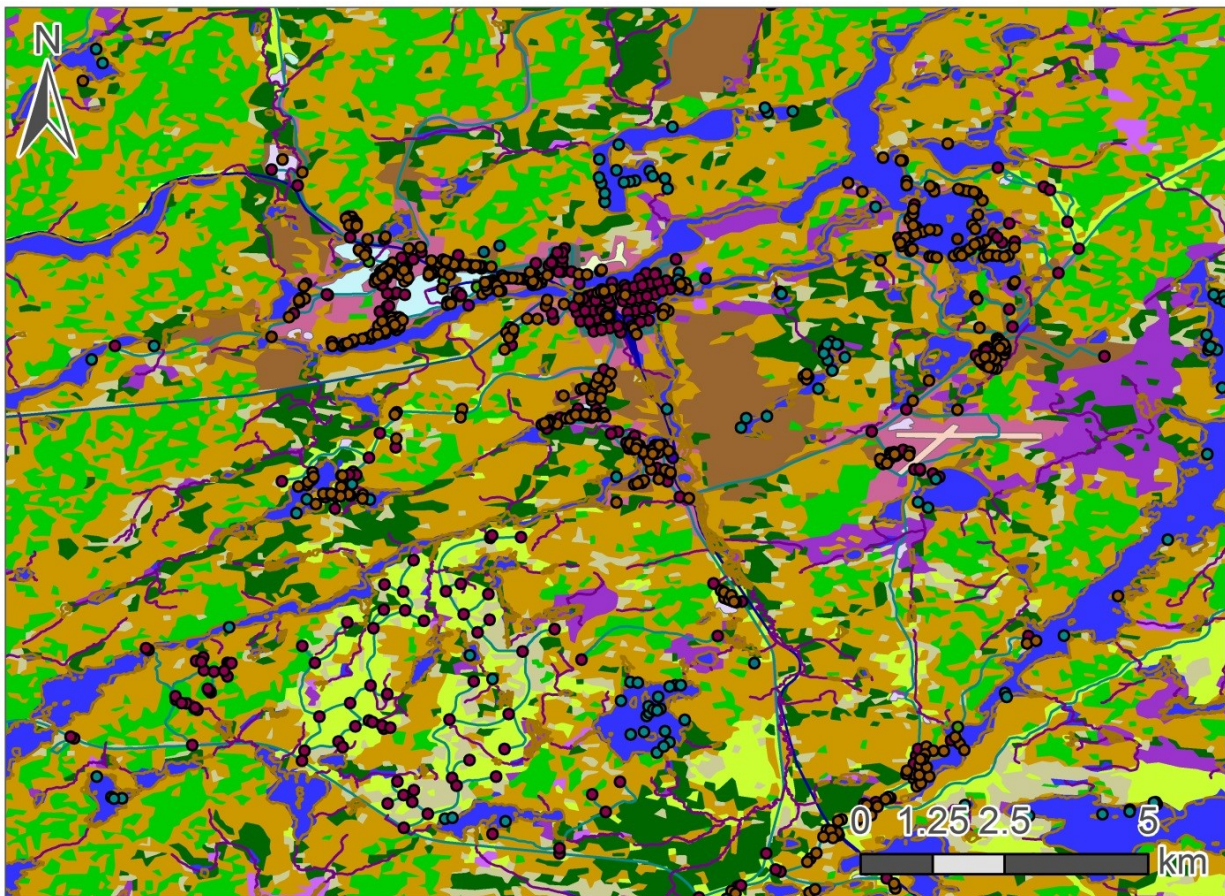
Figure 2-2. Sample of the CanVec+ and LandCover 2000 databases for Chapleau, Ontario.
Sample of the CanVec+ database for Chapleau, Ontario and surrounding area. Points, lines, and polygons for values relevant to this study are shown from the CanVec+ dataset. Land cover polygons from the LandCover 2000 dataset are shown in shades of green, brown, and purple. *Contains information licensed under the Open Government Licence – Canada.*

2.2   Interface Definitions

For the purposes of this study, a structure-based approach (see section 1.3.3) was taken to map the interface areas of Canada. Here, the interface is defined as the area of wildland fuels surrounding any potentially vulnerable structure (i.e. a fuels-focused, not a structure-focused definition as discussed in Platt (2010)). Specific definitions are outlined below for fuels, structures, buffer distance and the resultant interface areas. These definitions are based on the available data, the intended applications of the interface maps, and existing definitions.

2.2.1   *Fuels Definition*

Since a structure-based approach is taken in this study, thresholds of vegetation densities in broad areas are avoided (e.g. using >50% coverage of wildland vegetation in a census block as in Radeloff *et al.* (2005); see Table 1-1). All wildland fuels that are burnable by fire (i.e. "wildland fuels") are included as input data. Any fuels mapped in LC2000 which are near an interface structure (see following sections on structures and buffer definitions) are considered interface areas. No minimum fuel cluster size was used[5] (e.g. as in Chas-Amil *et al.* (2013) a minimum continuous fuel area of 500 ha was required for an area to be WUI). A minimum threshold was not used primarily because: 1) smaller areas of fuel can still impart fire risk to nearby structures, and 2) details of the fuel map could result in the removal of functionally continuous fuels (e.g. a small dirt road or some other linear feature would result in a break in the fuel map, but on the ground, a small fuel break may not appreciably affect fire spread).

Wildland fuels taken from the LC2000 dataset include: shrublands, grasslands, vegetated wetland, tundra, herb, and forest (all types). Following other studies (Radeloff *et al.* 2005; Wilmer and Aplet 2005; Theobald and Romme 2007; Lampin-Maillet *et al.* 2010), non-burnable lands such as croplands are not included. Wetlands are typically excluded in previous studies (as in Radeloff *et al.* (2005)), but are occasionally included (as in Theobald and Romme (2007)). In this study true wetlands are removed, but vegetated wetlands are included since they do burn (Kirby *et al.* 1988; Turetsky *et al.* 2004; Kobziar *et al.* 2011). Several other land cover types were excluded since they represent non-fuel (bare soil, developed land, exposed land, rock, snow/ice, barren, water), non-burnable fuel (croplands, pasture, sparse vegetation on rock), or

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[5] *However, it should be noted that the resolution of the fuel raster (LC2000) could be considered to impose a minimum threshold of fuel cluster size. Since small features (e.g. < 0.4 ha) are likely omitted from detection by the imagery and classification, pixels with small amounts of fuel would be classified as one of the non-fuel categories, resulting in small areas of fuel to be left out of this analysis.*

unknown land cover (cloud, shadow, unclassified, and no data). Grasslands were included as burnable wildland fuel, as they can exhibit fire behaviour that can impose a significant threat to structure (Forestry Canada Fire Danger Group 1992). However, long-distance spotting is not as much of a threat in grass fuels as compared to, for example, conifer fuels (Albini 1979, 1983; Beverly *et al.* 2010); this aspect is partially addressed in the reduced buffer distance for grassland (see sections 2.2.3 and 2.3.1).

2.2.2 Structures Definition

Since actual structure locations were used, subjective density thresholds are not required (e.g. using > 1 housing units per 16 ha as in Radeloff *et al.* (2005)); see Table 1-1 and section 2.1). Any structure in the CanVec+ dataset that may be damaged by wildland fire or may require protection from fire are included as input to the interface calculations. For each of the three interface types (i.e. WUI, WII, and infrastructure interface), different structure types were included. Table 2-1 provides the full list of structures used. In summary, for the WUI layer, the included structures were: "Residential area", most types of "Building", some "Places of Interest" (including stadiums, historic sites, campgrounds), and "Transportation" structures (e.g. railway station). For the WII layer, structures included were: any industrial types of "Building", some "Energy" entities such as oil and gas facilities, most "Industrial and Commercial Areas" including entities such as industrial and commercial areas, domestic waste, and lumber yard. For the infrastructure layer, the entities included were mostly linear infrastructure features such as pipelines (oil and gas, sewage), powerlines, communication line, railways, and roads. Features from the CanVec+ dataset that were not included in any of the three interface types were those which are unlikely to be damaged by wildland fire, unlikely to require suppression, or simply are not structural or infrastructure values relevant to the creation of these layers. The features not included are all features in the "Relief and landforms", "Map coverage limit", "Water saturated soils", "Toponymy" (i.e. named feature), and "Vegetation". Additionally, "Designated area" (in "Places of Interest") was not included because these areas do not represent structural or infrastructure values. "Ferry connection segment" (in "Transportation") was removed as ferry routes over waterbodies are not a potentially threatened value. "Junction" (i.e. road junction) and "Blocked passage" (i.e. along a road) (in "Transportation") were both removed because they both are features on roads which are already included. Furthermore, most features in the "Hydrography" category were not included, with the exception of "Manmade hydrographic

Table 2-1. CanVec+ entities included as structures in this study.

CanVec+ entities (features of point, line, or polygon type) included as structures for the wildland-urban, industrial, or infrastructure interface.

CanVec+ Entity Name	Wildland-Urban Interface	Industrial Interface	Infrastructure Interface
Energy			
Gas and oil facilities		✓	
Pipeline – Multiuse/natural gas/oil/unknown			✓
Power transmission line			✓
Transformer station		✓	
Valve			✓
Wind-operated device		✓	
Industrial and Commercial Areas			
Domestic waste		✓	
Extraction area		✓	
Industrial and commercial area		✓	
Industrial solid depot		✓	
Lumber yard		✓	
Mine		✓	
Mining area		✓	
Peat cutting		✓	
Pit		✓	
Quarry		✓	
Places of Interest			
Amusement park	✓		
Botanical garden	✓		
Camp	✓		
Campground	✓		
Cemetery	✓		
Drive-in theatre	✓		
Exhibition ground	✓		
Footbridge			✓
Fort	✓		
Golf course	✓		
Golf driving range	✓		
Historic site/Point of interest	✓		
Lookout	✓		
Marina	✓		
Park/Sports field	✓		
Picnic site	✓		
Ruins	✓		
Shrine	✓		
Ski centre	✓		
Sports track/Race track	✓		
Stadium	✓		
Trail			✓
Zoo	✓		
Transportation			
Railway			✓
Railway Station	✓		
Railway Structure	✓		
Road segment			✓
Runway	✓		
Toll point			✓

| CanVec+ Entity Name	Wildland-Urban Interface	Industrial Interface	Infrastructure Interface
Hydrography			
Manmade hydrographic entity	✓		
Buildings and Structures			
Building - Arena	✓		
Building - Armoury	✓		
Building - City hall	✓		
Building - Coast guard station	✓		
Building - Community centre	✓		
Building - Courthouse	✓		
Building - Customs post	✓		
Building - Educational building	✓		
Building - Electric power station		✓	
Building - Fire station	✓		
Building - Gas and oil facilities building		✓	
Building - Highway service centre	✓		
Building - Hospital	✓		
Building - Industrial building		✓	
Building - Medical centre	✓		
Building - Municipal hall	✓		
Building - Other	✓		
Building - Parliament building	✓		
Building - Penal building	✓		
Building - Police station	✓		
Building - Religious building	✓		
Building - Satellite-tracking station	✓		
Building - Sportsplex	✓		
Building - Unknown	✓		
Chimney - Burner		✓	
Chimney - Flare stack		✓	
Chimney - Industrial		✓	
Chimney - Unknown		✓	
Cross	✓		
Navigational aid	✓		
Parabolic antenna	✓		
Pipeline (Sewage/liquid waste)			✓
Residential area	✓		
Silo	✓		
Tank - Horizontal, unknown	✓		
Tank - Unknown, unknown	✓		
Tank - Vertical, other	✓		
Tank - Vertical, unknown	✓		
Tank - Vertical, water	✓		
Tower - Clearance	✓		
Tower - Communication	✓		
Tower - Control	✓		
Tower - Firebreak	✓		
Tower - Lookout	✓		
Transmission line - Telephone, other			✓
Underground reservoir	✓		
Well - Petroleum		✓	
Well - Unknown or Water	✓		

entity" which includes values (e.g. docks, dams) which are in many cases less vulnerable, but may still require fire protection in some cases.

2.2.3   Buffer Definition

The buffer distance is the one element in this study with a subjective threshold for the WUI definition. A buffer of 2400 m was chosen for two reasons: 1) this distance is used in WUI mapping literature frequently (used in: Radeloff *et al.* (2005), Stewart *et al.* (2007), Haight *et al.* (2004), Maranghides and Mell (2012), Maranghides and Mell (2011), Platt (2010), Rozmajzl (2012), Hammer *et al.* (2007), Zhang *et al.* (2008), Bar-Massada *et al.* (2013), Gowman (2013), Thomas and Butry (2014), Theobald and Romme (2007), and Tully (2013); see Table 1-1) since it is said to represent the distance a firebrand can travel from a wildland fire and ignite a structure, and 2) this distance is an appropriate match to the spatial scale and the management applications of the interface maps in this study (e.g. values protection, fire management planning, and fuels treatments; see section 4.2 and discussions within Theobald and Romme (2007) and Platt (2010)). Both larger and smaller buffer distances have been used in other studies (e.g. Theobald and Romme (2007) used 3200 m, 1600 m, and 800 m; Wilmer and Aplet (2005) used 800 m; Beverly *et al.* (2010) used 500 m). However, the 2400 m buffer distance not only is the most frequently used buffer distance in WUI mapping and matches a variety of management applications (as stated above), but it also errs on the side of caution by using one of the larger distances, providing an estimate of interface area representing something closer to a "worst case scenario" of fire behaviour (i.e. spread and firebrand production and transport) (Porterie *et al.* 2007).

The 2400 m buffer distance is actually a maximum potential distance, and the actual buffer distance is modified by fuel type, fuel spatial arrangement, and aggregation of fuels (discussed in section 2.3). Using this variable-width buffer instead of a static-width buffer (referred to as "isometric buffering") allows a much more accurate estimation of the interface area and has been used in previous interface mapping studies (Theobald and Romme 2007; Gowman 2013). For example, a structure entirely surrounded by fuel that is potentially high hazard (e.g. a continuous conifer stand) would have a buffer distance of 2400 m, but a structure with lower hazard fuels (e.g. deciduous forest), less continuous fuels, or more non-fuel (e.g. lakes) surrounding it would have a much smaller buffer. Using the variable-width buffer will, in almost all cases, result in a smaller interface area. However, the area mapped as interface is a

much more accurate representation of the interface area. In the previous example, if a static-width buffer was used, both the structure with the continuous conifer fuels and the structure with discontinuous deciduous fuels would be assigned an equal amount of interface area, which does not reflect the reality of the differences in hazard and suppression difficulty of the two areas. Figure 2-3 compares basic isometric buffering with variable-width buffering for a small community and provides an example of how the specific fuels surrounding each structure modifies the variable-width buffer.
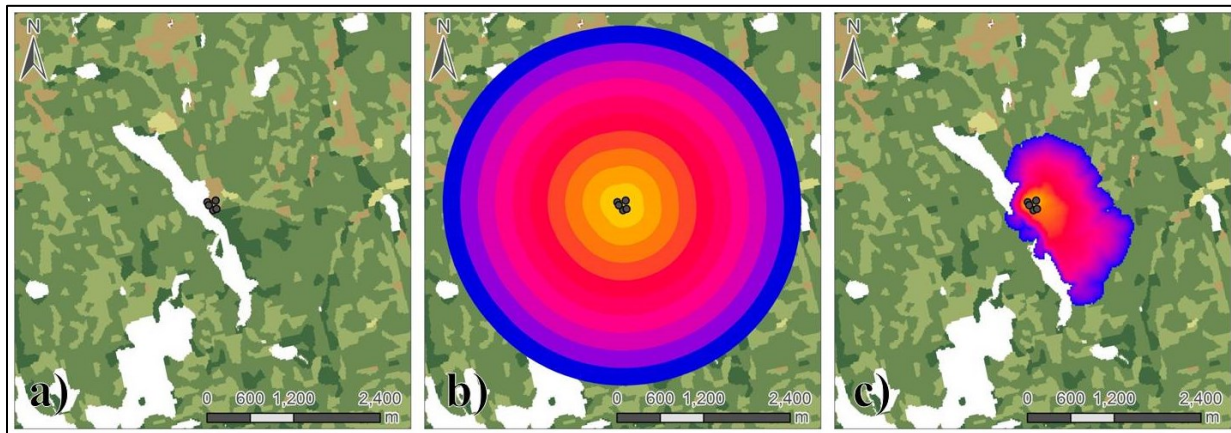
**Figure 2-3. Maps comparing isometric and variable-width buffers.**
Maps of a small area of Canada, **a)** showing structures (grey points in centre of map) and fuels (i.e. land cover; green and grey polygons), and then the resultant buffer (colour gradient from yellow to blue) using **b)** isometric (i.e. a static-width buffer) or, **c)** a variable-width buffer. Isometric buffering produces regular circles around each structure, whereas the variable-width buffer conforms to the fuel cover type and non-fuel areas. *Contains information licensed under the Open Government Licence – Canada.*

2.2.4   Interface Definition

In this study, the interface is defined as the area of wildland fuels (to a maximum of 2400 m) surrounding the location of a potentially vulnerable structure. To avoid subjective divisions based on density of interface areas, no distinction between intermix and interface (USDA and USDI 2001) situations will be made.

2.3   Interface Calculation

Producing the data for the interface maps had three main steps: 1) preparing the fuels layer, 2) preparing the structures layer, and 3) calculating the interface area. Figure 2-4 provides an overview of the workflow used to produce the data. Details of each of the three steps are described in the following sections (sections 2.3.1 to 2.3.3). Processing was done with ArcGIS (version 10.3) and R (version 3.0.1).

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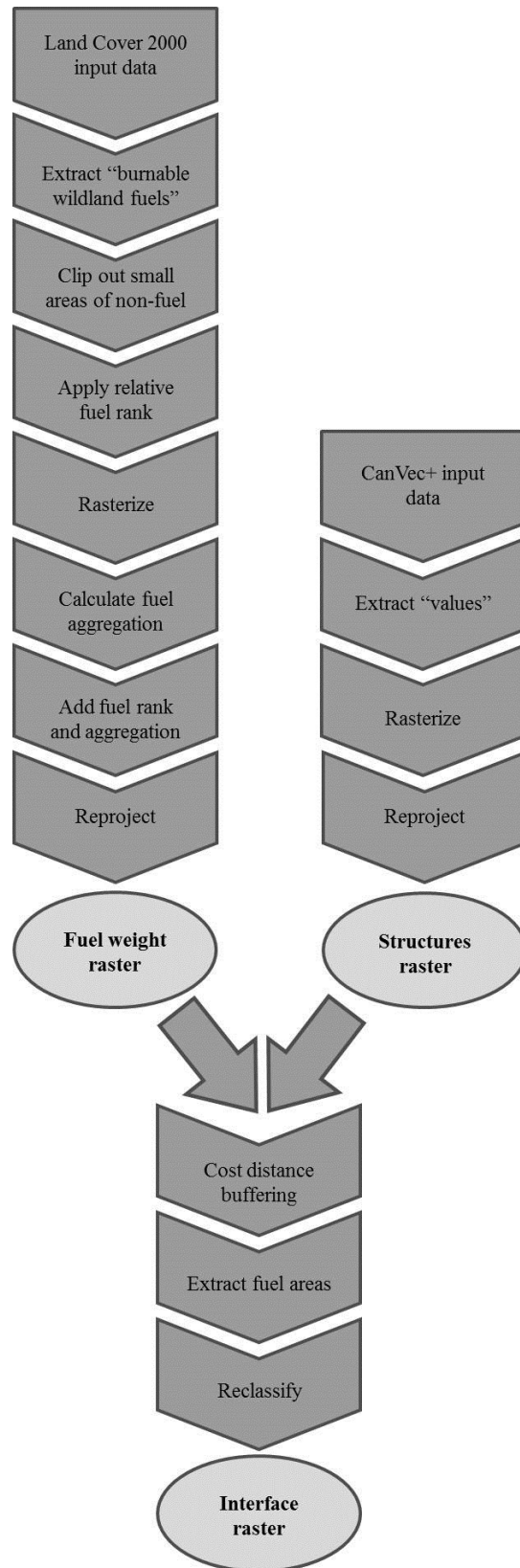
Figure 2-4. Workflow of the map production process for interface calculation.

2.3.1 Fuels Component

The wildland fuels (as defined in section 2.2.1) were extracted from the LC2000 dataset. Then, to ensure consistent topology between the land cover layer and the structures layer, small areas of non-fuel which were available in the CanVec+ dataset were removed from the land cover layer. The features removed included polygon features of: buildings and structures, energy, hydrology, industrial and commercial, places of interest, and transportation. This step removed a limited amount of area, with the majority of corrections from the hydrology features.

Fuels were then grouped into categories based on their relative maximum potential "hazard" (i.e. their difficulty of suppression), as shown in Table 2-2. This ranking relied on potential fire behaviour and suppression difficulty based on the Canadian Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). Categories were limited to five in order to reduce the number of subjective divisions. These rankings permitted a more accurate estimate of the actual interface area (see section 2.2.3 on buffer definition) than would have been obtained using a Boolean (i.e. fuel/not fuel) system. The ranking method is similar to what has been used in previous studies (Menakis *et al.* 2000; Haight *et al.* 2004; Theobald and Romme 2007; Gowman 2013).

An additional fuel layer was produced which consisted of an assessment of fuel horizontal connectivity. This layer uses the aggregation index (AI), which is outlined in He *et al.* (2000). In summary, the AI is a measure of the degree of what is referred to as contagion, connectivity, dispersal, or aggregation of similar cell types (Wang *et al.* 2014a) for raster data across a landscape and is stated as:

$$AI = (e_{i,i} / max\_e_{i,i}) \, 100$$

Where $e_{i,i}$ is the number of shared edges for class *i* in the area of interest and $max\_e_{i,i}$ is the maximum potential number of shared edges (i.e. maximum aggregation of cells where all cells are clumped together). The $max\_e_{i,i}$ variable is defined as[6]:

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[6] *The $max\_e_{i,i}$ equation conditions here are the corrected version of those published in He et al. (2000). From He et al. (2000), their second conditional statement (m < n) was corrected to m ≤ n (and m > 0 was added to make the conditional statement explicit). Additionally, from He et al. (2000), the third conditional statement (m ≥ 0) was corrected to m > n. These corrections are used in landscape metric tools such as Fragstats. Fragstats could not be used here due to the large scale and fine resolution, and the need for analysis on a moving window basis with a batch of files. The built-in function to calculate AI with the SDMTools package for R was not used because there are multiple errors in the calculation; however the PatchStat function in the SDMTool package was used to calculate patch statistics.*

Table 2-2. Land cover types, equivalent fuel types, and rankings used in this study.
Land cover vegetation types from the Land Cover 2000 (LC2000) dataset used in this study along with the relative fuel rank categories and their potentially equivalent Fire Behavior Prediction (FBP) System fuel type (Forestry Canada Fire Danger Group 1992) for which the rankings were based upon. FBP fuel types referred to include: C1 (Spruce-Lichen Woodland), C2 (Boreal Spruce), C3 (Mature Jack or Lodgepole Pine), C4 (Immature Jack or Lodgepole Pine), C5 (Red and White Pine), C6 (Conifer Plantation), C7 (Ponderosa Pine – Douglas-Fir), M1 (Boreal Mixedwood – Leafless), M2 (Boreal Mixedwood – Green), D1 (Leafless Aspen), O1 (Grass), and N/A is not applicable (no equivalency in FBP).

LC2000 Vegetation Cover	Equivalent FBP Fuel Type	Fuel Rank
200 (Forest)	C1-7, D1, M1-4	
210 (Coniferous forest)	C1-7	
211 (Conifer dense)	C2-6	1
212 (Conifer open)	C2-7	
213 (Conifer sparse)	C1, C7	
230 (Mixedwood)	M1, M2	
231 (Mixedwood dense)	M1, M2	2
232 (Mixedwood open)	M1, M2	
233 (Mixedwood sparse)	M1, M2	
220 (Deciduous forest)	D1	
221 (Broadleaf dense)	D1	
222 (Broadleaf open)	D1	
223 (Broadleaf sparse)	D1	3
50 (Shrubland)	N/A	
51 (Shrub Tall)	N/A	
52 (Shrub Low)	N/A	
110 (Grassland)	O1	
81 (Wetland - Treed)	N/A	
82 (Wetland - Shrub)	N/A	
101 (Tussock graminoid tundra)	N/A	
102 (Wet sedge)	N/A	4
103 (Moist to dry non-tussock graminoid/dwarf shrub tundra)	N/A	
104 (Dry graminoid prostrate dwarf shrub tundra)	N/A	
83 (Wetland - Herb)	N/A	
100 (Herb)	N/A	5

$$\text{max\_e}_{i,i} = 2n(n-1) \qquad\qquad \text{when m} = 0$$

$$\text{max\_e}_{i,i} = 2\,n\,(n-1) + 2m - 1 \qquad\qquad \text{when m} > 0 \text{ and m} \leq \text{n}$$

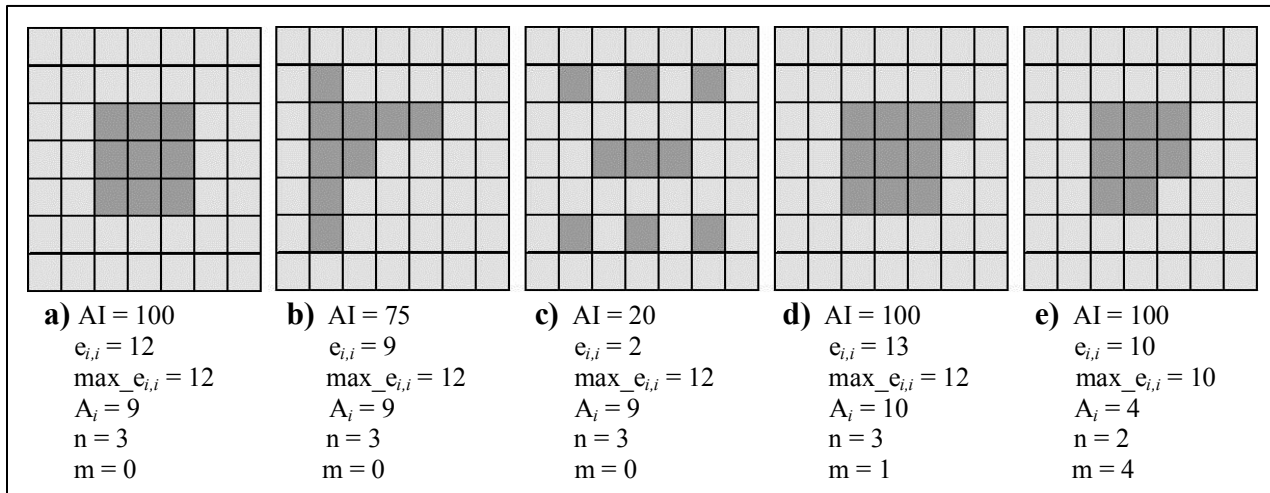$$\text{max\_e}_{i,i} = 2\,n\,(n-1) + 2m - 2 \qquad\qquad \text{when m} > \text{n}$$

With *n* representing the number of cells along the side of the largest square that can be formed with A_i (the total number of cells of class *i*):

$$n = |\sqrt{A_i}\,|$$

and *m* representing the difference between the number of cells (A_i) and the largest square that can be formed with those cells (n^2):

$$m = A_i - n^2$$

AI ranges from 0 (no shared cell edges) to 100 (completely aggregated arrangement with maximum number of shared cell edges). Figure 2-5 provides examples of three varying spatial arrangements of one class of cell (grey cells = class *i*), the corresponding AI, and the associated calculation values.

a) AI = 100
$e_{i,i} = 12$
$\text{max\_e}_{i,i} = 12$
$A_i = 9$
n = 3
m = 0

b) AI = 75
$e_{i,i} = 9$
$\text{max\_e}_{i,i} = 12$
$A_i = 9$
n = 3
m = 0

c) AI = 20
$e_{i,i} = 2$
$\text{max\_e}_{i,i} = 12$
$A_i = 9$
n = 3
m = 0

d) AI = 100
$e_{i,i} = 13$
$\text{max\_e}_{i,i} = 12$
$A_i = 10$
n = 3
m = 1

e) AI = 100
$e_{i,i} = 10$
$\text{max\_e}_{i,i} = 10$
$A_i = 4$
n = 2
m = 4

Figure 2-5. Raster examples of various landscape aggregation index (AI) values.
Aggregation index (AI) for five example raster areas with a completely aggregated pattern of dark grey cells in **a)**, **d)**, and **e)**, less aggregated in **b)**, and very low aggregation (i.e. dispersed) pattern in **c)**. Associated variables calculating AI are stated below each figure. AI is aggregation index, $e_{i,i}$ is number of shared edges within a class, $\text{max\_e}_{i,i}$ is the maximum potential number of shared edges given the number of cells, A_i is the total number of cells of a class, n is the number of cells of the side of the largest square that can be formed with the number of cells, and m is the difference between A_i and n^2.

In this study, the AI was calculated on a rasterized version (cell size of 0.0002 decimal degrees) of the fuel layer, and considered for all fuels together, not by each fuel type. AI was assessed on a 5x5 cell focal moving window for each raster cell across the country using R (version 3.0.1). The PatchStat function in the SDMTools R package (VanDerWal 2014) was

used to calculate A_i and $e_{i,i}$. AI values were put into three categories: AI values above 90 were "high" and given a rank of 0, AI values between 0 and 90 were "low" and given a rank of 1, and AI values of 0 were "no aggregation" and given a rank of 2. For each raster cell, these ranks were added to the 1-5 ranks of the fuel land cover (categories as in Table 2-2), resulting in fuel weight categories from 1 to 7 to form a weighted raster layer for variable-width buffering process. As an example, a raster cell with a conifer fuel type (rank of 1) and a "high" AI (rank of 0) result in a value of 1 for that cell's fuel weight value. For reference, the R code to calculate AI is included in Appendix 1.

The AI has been used in previous WUI mapping studies (Lampin-Maillet *et al.* 2010; Galiana-Martina *et al.* 2011; Herrero-Corral *et al.* 2012; Bouillon *et al.* 2014), and similar functions are used in other studies (Chas-Amil *et al.* 2013; Tully 2013). This index allows a way to classify high fuel connectivity and low fuel connectivity, providing a proxy for the ease of fire spread across the landscape (Zhang *et al.* 2008; Lampin-Maillet *et al.* 2010). It should be noted that small-scale connectivity (i.e. sub-pixel) is not considered with this calculation, despite the importance of small scale fuel characteristics affecting fire behaviour (Forestry Canada Fire Danger Group 1992; Burton *et al.* 2008). Despite the limitations, including the AI does effectively add useful information that would otherwise not be included in the calculation of the interface areas.

The fuels layer (consisting of fuel weight values from the combination of AI and fuel rank from cover types) was reprojected from the original NAD 1983 CSRS projection (in decimal degrees) to Canada Lambert Conformal Conic (in meters) in order to use meters for the cost distance procedure (section 2.3.3) and for display purposes.

2.3.2   *Structures Component*

Structure locations were extracted from the CanVec+ dataset into three separate layers (one for each of the: WUI, WII, and infrastructure interface) based on the categorization outlined in Table 2-1. Since subsequent steps (section 2.3.3) require raster data, structure layers were converted from lines, points, and polygons to raster (assigning structure values to a raster cell with any small line, single point, or small polygon within the cell).

As with the fuels layer, the structures layers were reprojected from NAD 1983 CSRS projection (in decimal degrees) to Canada Lambert Conformal Conic (in meters).

2.3.3 Fuels and Structures to Interface

Fuels and structures layers were combined for the third and final stage of processing (i.e. calculating the interface areas) (Figure 2-4, Figure 2-6a). For each interface type (WUI, WII, infrastructure interface), the relevant structure layer was overlaid on the fuels layer. The variable-width buffer was then calculated around each structure (Figure 2-6b) using a "cost distance" procedure in ArcGIS. This cost distance buffer requires a point to begin the cost distance calculation (here, a structure cell of the structure raster), and then uses a "cost raster" (in this case, the fuel weight raster) to calculate the cost distance radiating out in all horizontal directions (on a cell-by-cell basis as rook's case) from the input point. Movement to the next cell can be thought of as having a "cost", with the actual cost of moving to that cell weighted by the values of the cost raster (i.e. the fuels). The distance calculation continues until a maximum distance is reached; which in this case is 2400 m (as discussed in section 2.2.3). As an example, suppose the cost distance procedure is calculating the cost distance for a structure surrounded by 600 m of a mixedwood forest stand with high AI (giving it a fuel weight of 2). This 600 m really "costs" 1200 m (600 m x 2 fuel weight), due to the fuel weight. Then suppose beyond the mixedwood stand there is a dense coniferous forest with high aggregation (fuel weight of 1), which allows the buffer to extend another 1200 m (1200 m x 1 fuel weight) until it reaches the maximum "cost weighted distance" of 2400 m. While the cost weighted distance is 2400 m, the physical buffer distance is actually only 1800 m (600 m from the mixedwood + 1200 m from the conifer forest) in this example. In reality, the fuel patterns are more complex, with patches of many different fuel weights arranged in varying patterns around structures. Overall, the result is a variable-width buffer with an appropriate shape and distance around each structure, depending on the fuel weight and arrangement (see Figure 2-3 and Figure 2-6 for illustrations of the variable-width buffering).

It should be noted that though water and other non-fuel areas (see section 2.2.1) are not considered fuel, non-fuel was given a fuel rank of 10 in the cost distance calculations. This reflects the spreading and spotting potential of a wildfire; a single cell of non-fuel does not cause fire spread to stop, but it does have a high "cost" associated with the cost distance calculation. These non-fuel areas were then removed, leaving in only fuel areas. The cost distance values were then reclassified into "interface" (value of 1) or "not interface" (value of 0) for the final interface maps (Figure 2-6c).

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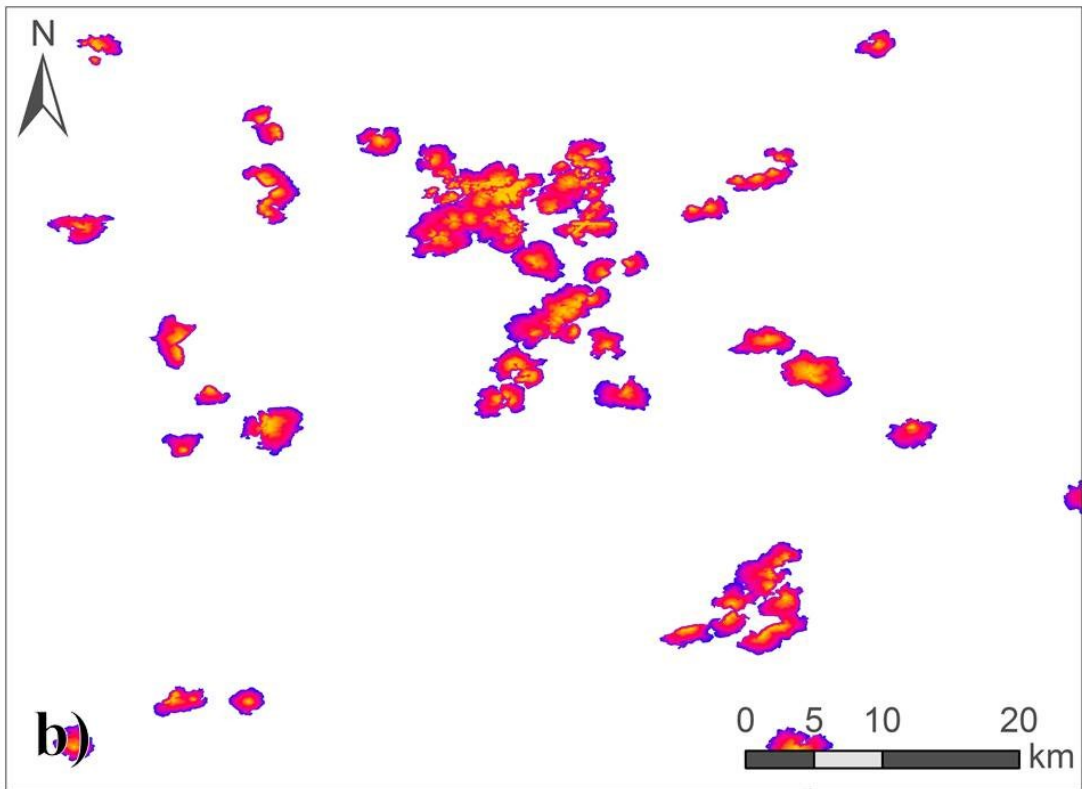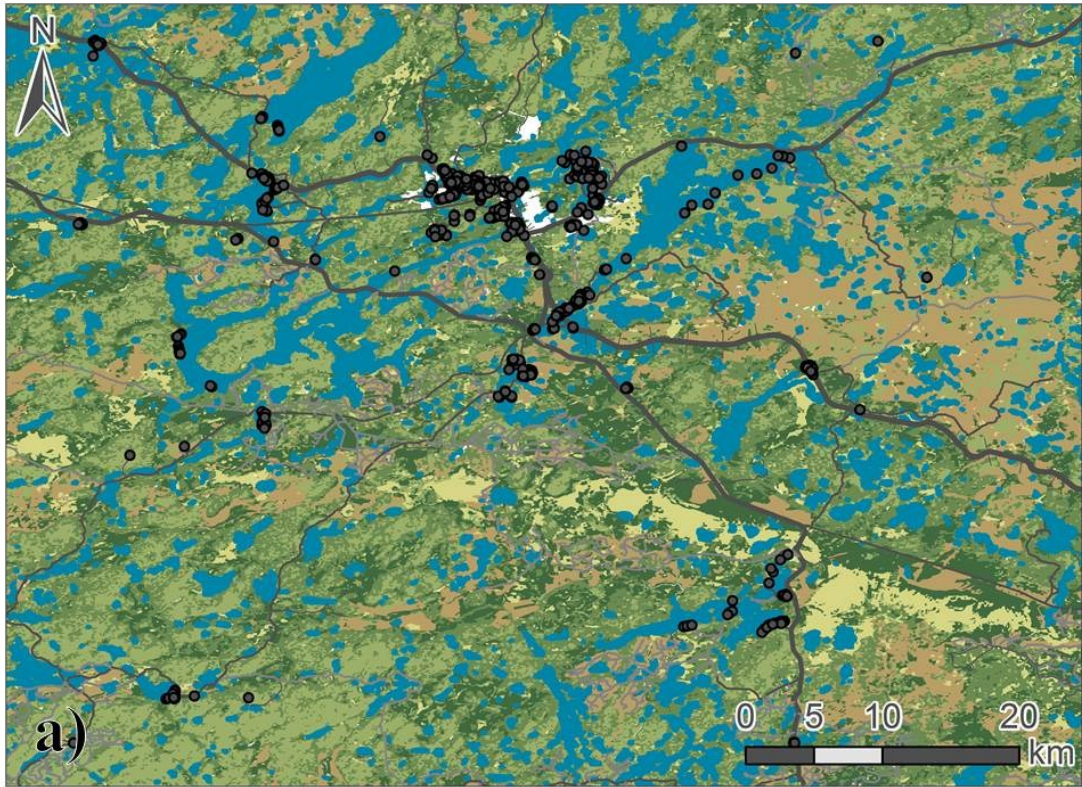
Figure 2-6. Maps showing cost distance variable-width buffering process.
Maps of Chapleau, Ontario and surrounding area showing: **a)** fuel land cover (shades of green-brown) and water (blue) with structures, roads, and railways (all shown in dark grey) overlaid, **b)** for the same area, the raw variable-width buffer based on the cost distance mapping around "urban" structures, and **c)** the same buffer area, but with non-fuels clipped out and cost distance values reclassified to interface/not interface, forming the final wildland-urban interface area (purple) for this sample map. This example shows only wildland-urban interface for simplicity, but the same process is used for wildland-industrial interface and infrastructure interface.

Removing the buffered areas that are non-fuel from the final interface areas reflects the definition of the interface and the associated practical applications. The interface definition focuses on the wildland fuels. If there is no fuel, there is no interface. Non-fuel areas will not carry fire and the practical applications (e.g. fuel treatments, FireSmart, fire suppression; see section 4.2) do not apply to non-fuel areas. Many previous studies using buffering do not remove these non-fuel areas from the buffer, resulting in an overestimate of interface area. For example, in Theobald and Romme (2007), a similar variable-width buffer was used, but the entire buffer area was considered interface. Using those methods, it is possible to have a structure mostly surrounded by water or low hazard fuel but have a significant area of interface surrounding it. Comparing Figure 2-6b and Figure 2-6c provides an example of how the removal of non-fuel areas from the buffers adjusts the interface area.

2.4 Assumptions and Sources of Error

This study assumes that all structures included as interface structures are easily and equally ignitable; in reality, structure ignition is variable and complex (Cohen 2000; Caballero *et al.* 2007; Mell *et al.* 2010; Calkin *et al.* 2014). This is a common assumption for interface mapping (Menakis *et al.* 2000; Radeloff *et al.* 2005; Theobald and Romme 2007) and simplifies the data requirements for mapping the interface. However, structures included as interface structures were only included if they could potentially be damaged by wildfire or would receive fire suppression in a firefighting situation (Table 2-1). Structure ignition and flammability could later be included as part of an interface risk-focused analysis based on this map (see discussion of future research in section 5.1).

Minor errors in the results of this study may be introduced when converting vector data to raster (mentioned in Stewart *et al.* (2009)) resulting in a loss of accuracy; but on a national scale, these errors are inconsequential. Errors may also be introduced through the input data including errors from accuracy or precision (e.g. positional accuracy, issues with topology, classification errors of commission or omission), or from lack of data updates. Use of these interface maps must take these potential errors into consideration.

As an example of the importance of data accuracy and updates, a newly built subdivision would not be included in the CanVec+ structure data. A specific example of this situation is found in Fort McMurray, Alberta, an area that has grown quickly in recent years. Figure 2-7 depicts the interface area (all three types) for Fort McMurray and surrounding area. In the first image (Figure 2-7a) the original CanVec+ structure data is overlaid, and in the second image (Figure 2-7b) a manually updated version of the structure data and updated interface maps are shown. The CanVec+ dataset had only updated the road network layer for the newly developed area, resulting in infrastructure interface area to be mapped in the first image, but with large areas of WUI missing. Updating the urban area resulted in more than a doubling of WUI area in the spatial extent shown in Figure 2-7. In the May 2016 wildfires, some areas mapped as new WUI were impacted and saw structural losses. These and other missing interface areas are not included in the final maps or area estimates.

The fuels layer (LC2000 data) is compiled from data over multiple years from 1996-2005, but for the purposes of this study, fuels are assumed to be representative of the actual current fuel conditions. Assigning fuel rankings (section 2.3.1) has the benefit of downgrading
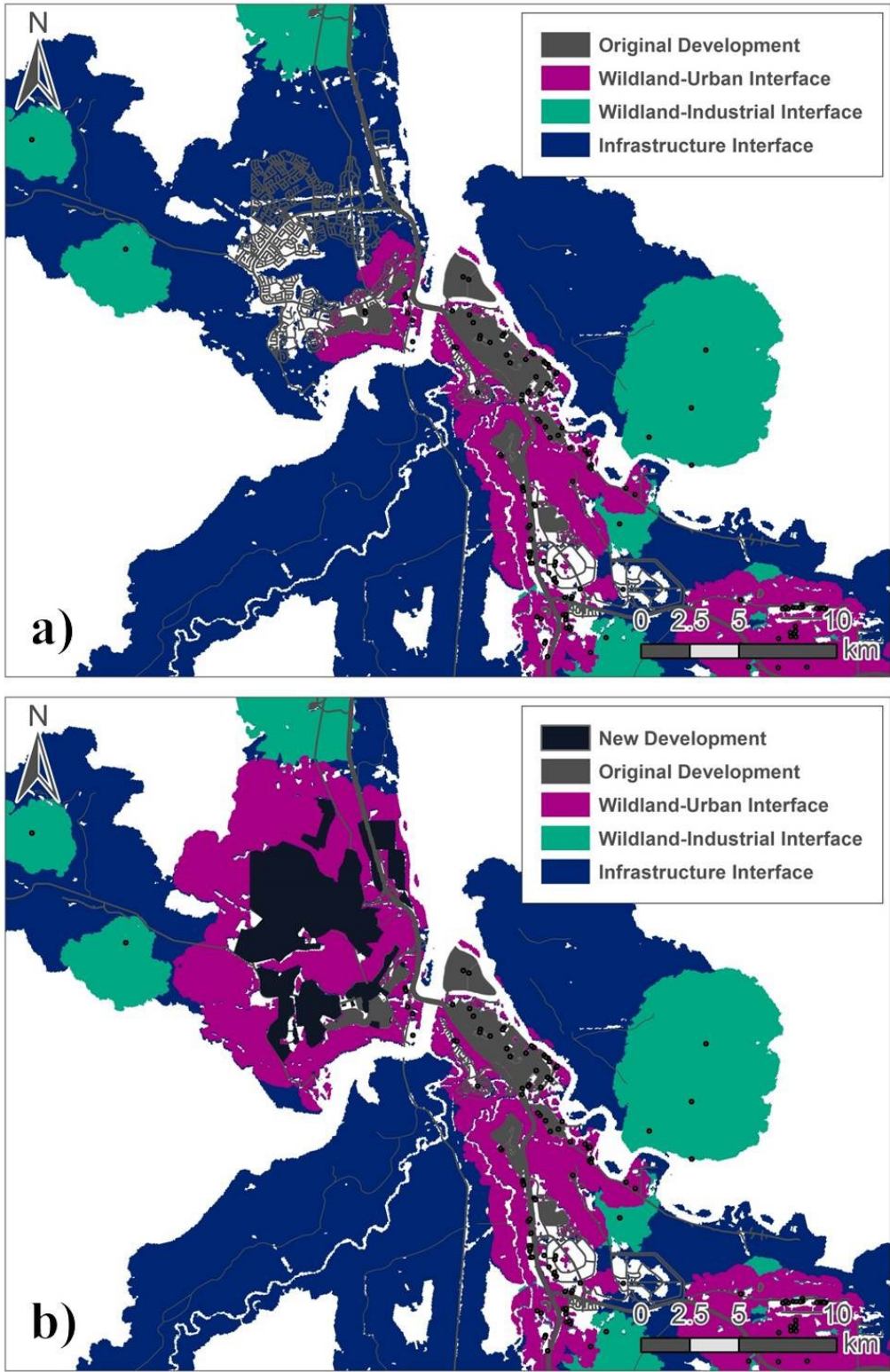
Figure 2-7. CanVec+ structure data compared to more recent urban development maps.
Two maps depicting **a)** the CanVec+ structure data for the area of Fort McMurray, Alberta, and **b)** the same area with new neighbourhoods added to the structure data from municipal lot information and remotely sensed images (Google Maps; accessed May 2016). Note that in the original structure data (a) the road network was up to date, resulting in infrastructure interface to be mapped in the new neighbourhood, but not wildland-urban interface.

the data to relative rankings, limiting some of the potential problems in the input data (Menakis *et al.* 2000). It is also assumed that the land cover data accurately represents the flammable fuels, with non-flammable areas masked out. In reality, the area surrounding homes and other structures can have abundant flammable fuels including landscaping vegetation, wood piles, or wildland fuels (Partners in Protection 2003), but from a land cover perspective, would likely be mapped as non-fuel unless the area included larger amounts of wildland fuels.

A limitation of using this data is use at an appropriate scale and for an appropriate purpose. For example, using this national map to inform a small-scale neighborhood interface assessment with no other input data would be unwise (discussed in Menakis *et al.* (2000)); the data precision is not high enough to do small-scale assessments. Any practical applications using this map should take into account the appropriate scale and limitations of the data, with the maps informing high-level decisions along with ancillary data with the appropriate scale and utility for the specific application. Section 4.2 will cover practical applications of these maps and outline the limitations of their use within these specific applications.

These interface maps are also not intended to be a structure-specific risk assessment, as they do not take into account varying fuels within wildland vegetation classes, weather, topography, aspect, structure characteristics and flammability, property FireSmart activities, and other smaller-scale factors. Even though an area on these maps may be classified as interface, it may have no actual risk, depending on the multitude of factors affecting risk. Alternatively, just because an area is not classified as interface on the maps does not mean there is no chance of threat or destruction from wildfire. These maps reflect what can be thought of the "worst-case scenario" conditions; risk within interface areas may be much higher or much lower depending on the season, fire weather conditions, fuel conditions, and small-scale fuel characteristics.

These maps focus on structural and infrastructure values, following the definition of what the interface is. However, these maps do not take into account other potential losses of non-structural, non-infrastructure values. These potential losses can include a wide variety of elements, including aesthetic, ecological, economic (including recreational loses and timber losses), and cultural values (Beverly *et al.* 2008; Hyde *et al.* 2013).

Furthermore, these interface maps are intended for use with applications to wildland fire. Though interface areas are also a hotbed for other human-natural issues such as biodiversity

impacts, forestry, wildlife management, land cover conversion, and habitat fragmentation (Radeloff *et al.* 2005; Theobald and Romme 2007; Bar-Massada *et al.* 2013; Bar-Massada *et al.* 2014), these maps have been defined by wildfire-focused parameters, and as such, may not be appropriate for use within these alternate applications.

3   INTERFACE MAPS AND ANALYSIS

In this chapter, interface maps are included for all three interface types together (i.e. the "wildland-human interface"), and also for each interface type individually (i.e. the wildland-urban interface (WUI), the wildland-industrial interface (WII), and the infrastructure interface). In addition to the interface maps, basic statistics for each map are presented, including: area, interface area as a percentage of total land area, and interface area as a percentage of burnable fuel area. Analysis of the spatial patterns of interface areas shown in these maps is performed. Furthermore, the relationships between fuels, structures, and interface, and also the relationships between fires and interface areas are examined.

3.1   Interface Maps

Nationally, there are 116.5 million ha of wildland-human interface area in Canada. A national map of the interface is shown in Figure 3-1. The interface area for each of the three interface types (WUI, WII, infrastructure interface) do overlap, and in Figure 3-1 are displayed with the WUI as the top layer, the WII as the next layer, and the infrastructure interface as the bottom layer. Individually, the WUI in Canada covers 32.3 million ha, WII covers 10.5 million ha, and infrastructure interface covers 109.8 million ha. Nationally, interface areas are located mostly in the southern portions of the country, with very limited areas in the northern portions. Of the 562 million ha of wildland fuels in Canada, 20.7% is mapped as wildland-human interface. Looking at total land area of Canada (842 million ha), 13.8% is interface. Table 3-1 presents the interface area (by area and by percent of land and percent of burnable fuel area) for the wildland-human interface, and also each interface type individually. More details for the spatial patterns and characteristics of each interface type individually are included in the following sections.
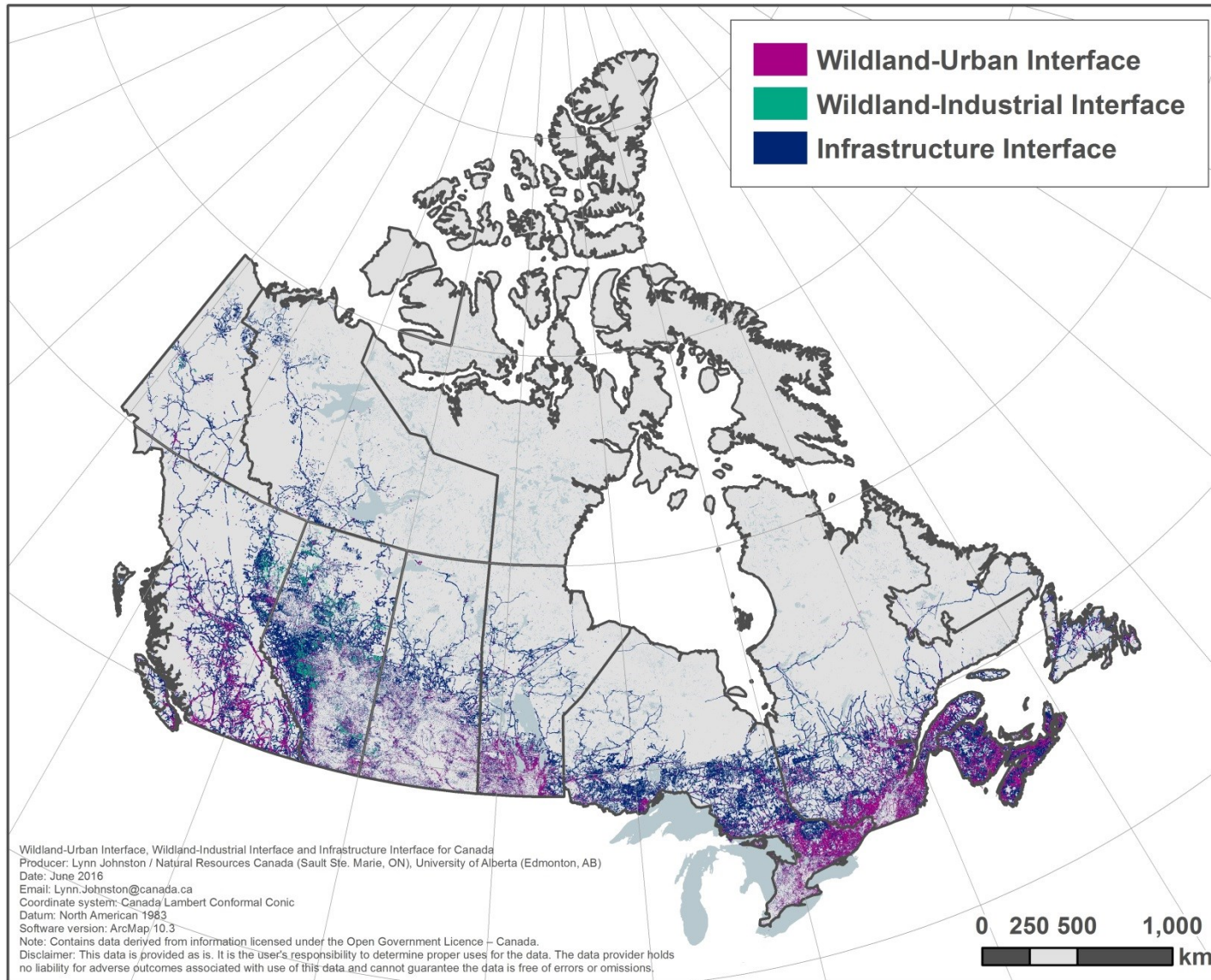
Figure 3-1. National map of the "wildland-human interface".

Map of the "wildland-human interface", i.e. the wildland-urban interface (WUI), wildland-industrial interface (WII), and the infrastructure interface together. The three layers overlap; for display purposes the WUI is given priority and is shown as the top layer, followed by the WII, with the infrastructure interface underneath. Hydrology is shown in light blue and Canada is shown in light grey.

Table 3-1. Interface by total area, percent of land area, and percent of fuel area.
Interface area (million hectares), and the percent of land area and percent of wildland fuel area which is mapped as interface; listed by interface type: wildland-urban interface (WUI), wildland-industrial interface (WII), infrastructure interface, and wildland-human interface (consists of the three interface types merged together). Note that areas do not sum to the composite wildland-human interface area due to overlap between the three layers.

Interface Type	Area (million hectares)	Percent of Land Area (%)	Percent of Wildland Fuel Area (%)
Wildland-Urban Interface	32.3	3.8	5.8
Wildland-Industrial Interface	10.5	1.3	1.9
Infrastructure Interface	109.8	13.0	19.5
Wildland-Human Interface	116.5	13.8	20.7

The national map presented in Figure 3-1 is for display purposes only and is not the full resolution map. The national rasters for each of the three interface types have a ~30 m cell size, with 29 to 37 billion cells each (3.4 to 4.3 GB 1-bit unsigned integer rasters each). Figure 3-2 illustrates the resolution of the interface maps for two local areas (for a small town and a large city). The same figure also provides an example of the differing patterns in the interface areas. In Figure 3-2a, the small town is surrounded mostly by wildland fuels, resulting in large, continuous interface buffers around structures. This area provides an example of a traditional interface community. In Figure 3-2b, the large city has limited and very dispersed fuels, resulting in small fragments of interface areas; the majority of this area would typically not be considered to have an interface fire issue[7]. Both maps are displayed at the same scale for comparison purposes.

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[7] *However, this is not to say there have been no interface fire threats; for example, the vegetated river valley of the large city of Edmonton, Alberta saw several small fires in 2002 which threatened homes (McGee 2007).*
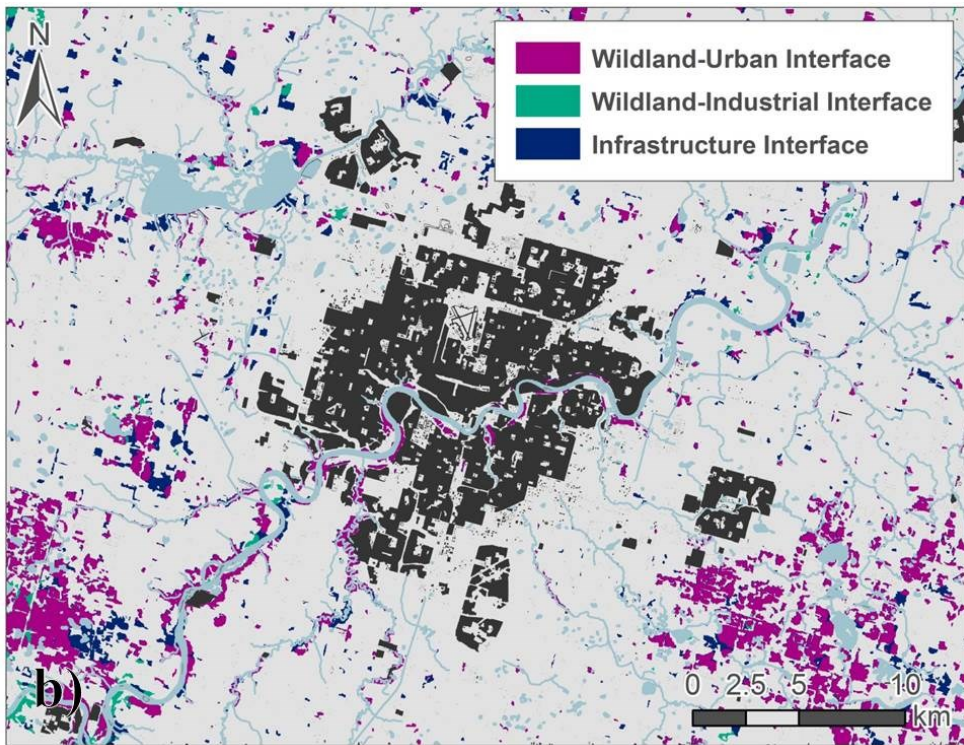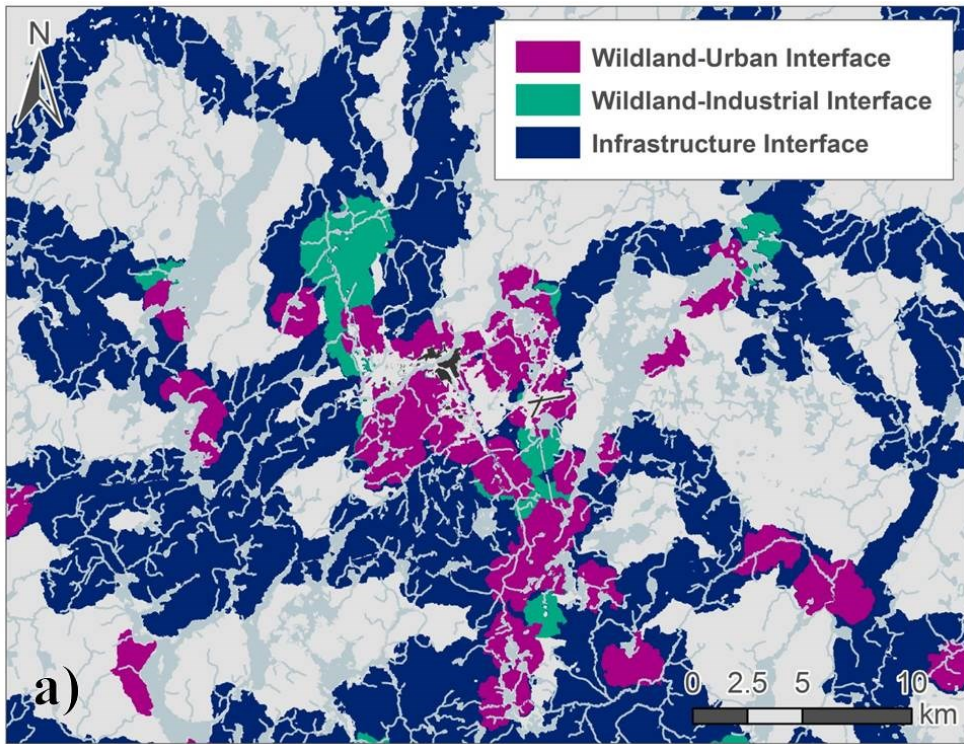
Figure 3-2. Small-scale interface maps for two local areas.
Interface areas (wildland-urban, wildland-industrial, and infrastructure interface) for two local areas: **a)** Chapleau, Ontairo, and **b)** Edmonton, Alberta. Structures are shown in dark grey and hydrology in light blue.
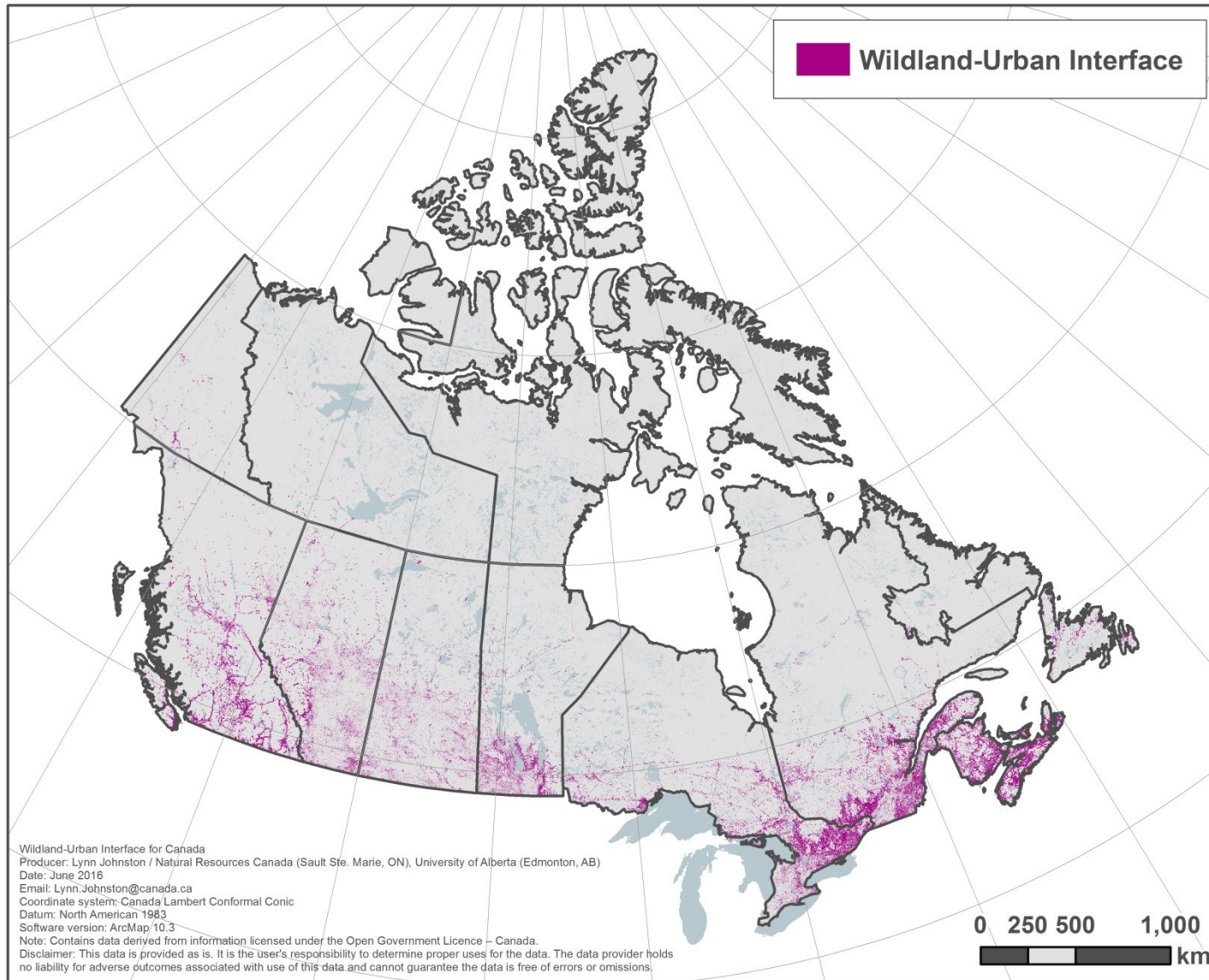
3.1.1 Wildland-Urban Interface

The WUI in Canada (Figure 3-3) covers 32.3 million ha across Canada. About 3.8% of land area and 5.8% of wildland fuel area is classified as WUI. As with the wildland-human interface, the majority of the WUI is distributed across in the southern portion of Canada, with extremely sparse WUI area in northern Canada. There is also typically a higher density of WUI in eastern Canada.

For a more detailed look at WUI area across Canada, section 3.2.1 presents WUI area as a raw area value and as a percentage of land area for each province and territory. Additionally, Appendix 2 presents WUI maps for each province and territory individually.

3.1.2 Wildland-Industrial Interface

The WII in Canada (Figure 3-4) covers 10.5 million ha across Canada. About 1.2% of land area and 1.9% of wildland fuel area is classified as WII. There is much less area of WII than WUI or infrastructure interface, and is generally quite dispersed. Alberta is the exception to this pattern, with larger amounts of WII area than other provinces and territories, and with some areas in a more clumped pattern.

For a more detailed look at WII area across Canada, section 3.2.1 presents WII area as a raw area value and as a percentage of land area for each province and territory. Additionally, Appendix 2 presents WUI maps for each province and territory individually.
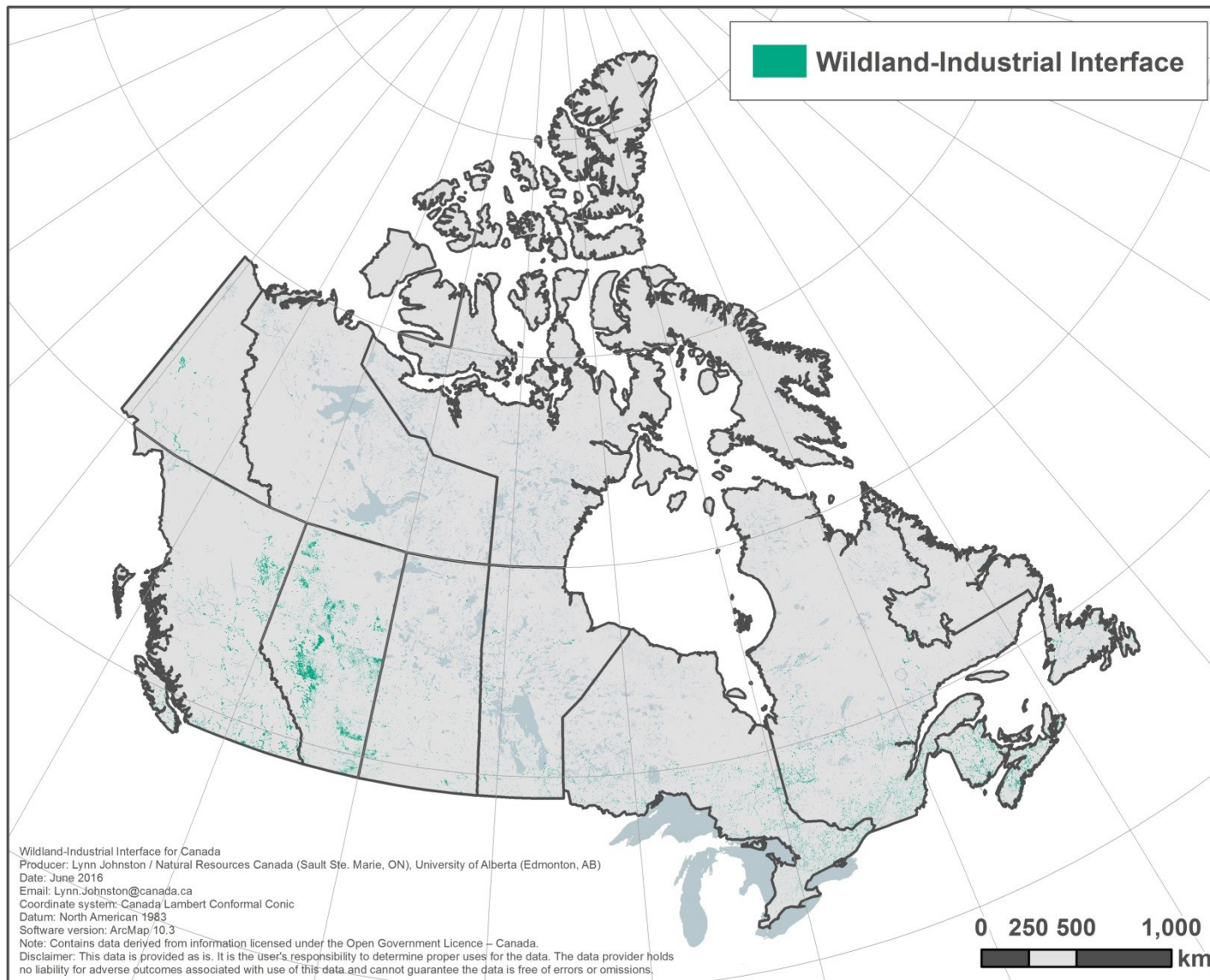
3.1.3 Infrastructure Interface

The infrastructure interface in Canada (Figure 3-5) covers 109.8 million ha across Canada. About 13.0% of all land area and 19.5% of wildland fuel area is classified as infrastructure interface. With the infrastructure interface covering much more area than the WUI and WII combined, it has a denser distribution across the country. As with the WUI, the southern part of Canada and eastern Canada has a higher infrastructure interface density.

For a more detailed look at infrastructure interface area across Canada, section 3.2.1 presents infrastructure interface area as a raw area value and as a percentage of land area for each province and territory. Additionally, Appendix 2 presents WUI maps for each province and territory individually.
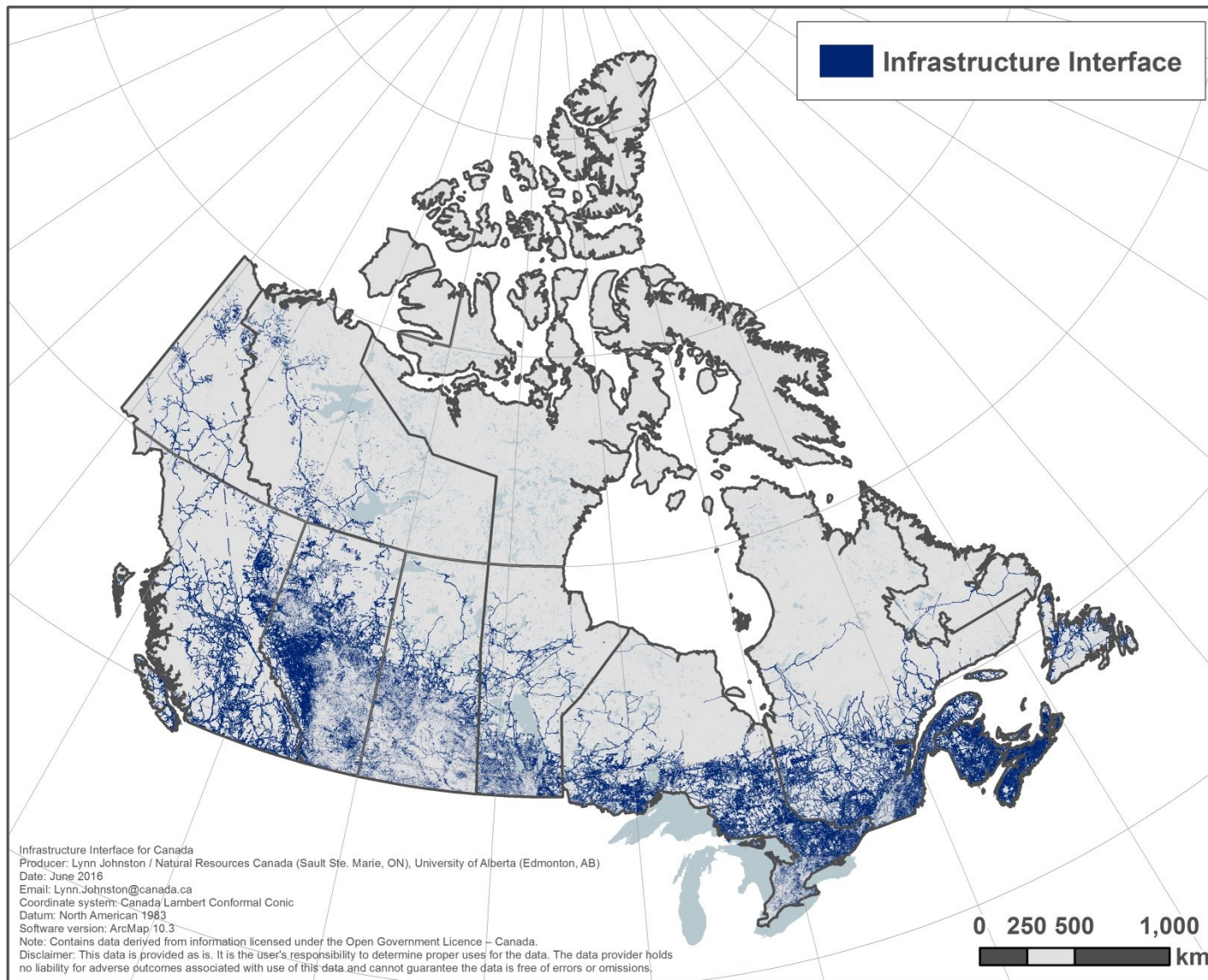
Figure 3-3. Wildland-urban interface national map.
Map of wildland-urban interface (WUI) for Canada. Hydrology is shown in light blue and Canada is shown in light grey.

Figure 3-4. Wildland-industrial interface national map.
Map of wildland-industrial interface (WII) for Canada. Hydrology is shown in light blue and Canada is shown in light grey.

Figure 3-5. Infrastructure interface national map.
Map of infrastructure interface for Canada. Hydrology is shown in light blue and Canada is shown as light grey.

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3.2   Spatial Patterns in Interface

In this section, details of the spatial patterns of interface area are presented for WUI, WII, and infrastructure interface. Each interface type will be considered individually as they each have different spatial patterns and practical applications.

3.2.1   Interface by Province

As mentioned in section 3.1, interface maps for each province and territory individually are presented in Appendix 2. To summarize the amount of area of interface by province and territory, total area of the three interface types (ha) and area of interface as a percentage of land area are presented in Table 3-2 for each province and territory and also nationally for Canada. For WUI, Quebec contains the largest area with 7.0 million ha, followed by 5.9 million ha in Ontario, and 5.5 million ha in British Columbia. However, when looking at WUI as a percentage of total land area, the dense arrangement of WUI in the provinces of Nova Scotia, Prince Edward Island, and New Brunswick results in very high values (45.1, 31.1, and 30.6%, respectively) in those three provinces. These three provinces are followed by Ontario (6.7%), British Columbia (6.4%), and Quebec (5.6%).

For WII, Alberta has the largest area with 3.4 million ha, then British Columbia with 1.8 million ha, Quebec with 1.5 million ha, and Ontario with 1.2 million ha. WII as a percentage of land area is highest in Nova Scotia (9.2%), followed by New Brunswick (7.9%), Alberta (5.5%), and Prince Edward Island (5.1%).

Looking at infrastructure interface, Ontario has the largest amount of area with 21.6 million ha, followed by Quebec (18.5 million ha), Alberta (18.0 million ha), and British Columbia (17.6 million ha). Patterns similar to what is seen for WUI and WII can be seen for infrastructure interface as a percentage of land area; Nova Scotia (77.0%), New Brunswick (66.5%), and PEI (38.6%) dominate and are followed by Alberta (29.0%), Ontario (24.5%), and British Columbia (20.5%).

Table 3-2. Provincial/territorial interface area for three interface types (by area, %).
Area of wildland-urban interface, wildland-industrial interface, and infrastructure interface as total area (ha) and interface area as a percentage of provincial or territorial land area (%) for each province and territory in Canada, and also for all of Canada.

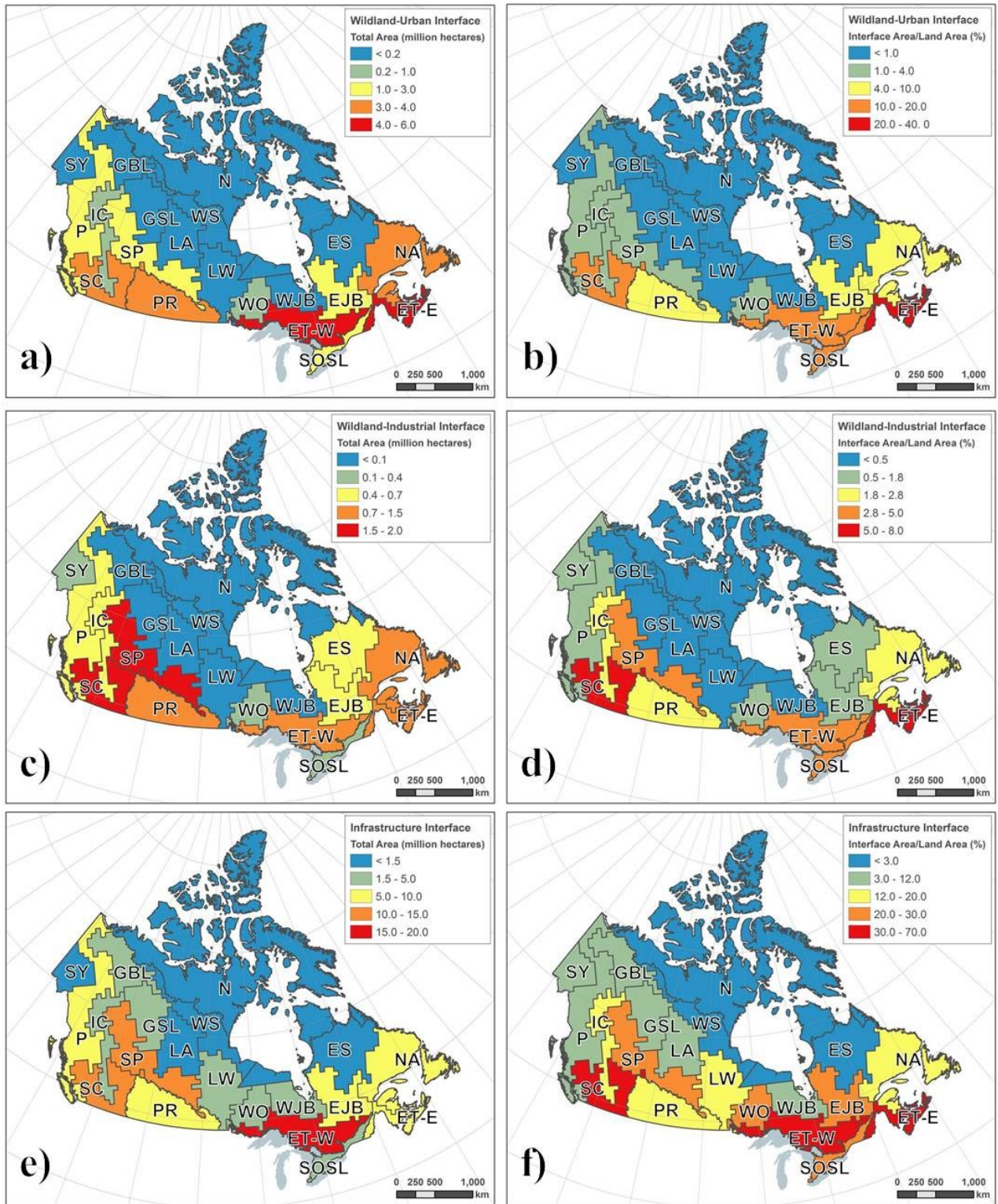|	Area (ha)			Interface Area/Land Area (%)		
	Wildland-Urban Interface	Industrial Interface	Infrastructure Interface	Wildland-Urban Interface	Industrial Interface	Infrastructure Interface
Alberta	3,165,144	3,409,839	18,027,267	5.1	5.5	29.0
British Columbia	5,520,686	1,762,337	17,617,488	6.4	2.1	20.5
Manitoba	2,282,665	389,097	7,023,709	4.4	0.7	13.5
New Brunswick	2,223,320	575,326	4,829,044	30.6	7.9	66.5
Newfoundland and Labrador	1,221,610	502,766	3,722,071	3.6	1.5	10.9
Northwest Territories	202,113	71,677	3,524,480	0.2	0.1	3.3
Nova Scotia	2,431,164	495,066	4,149,994	45.1	9.2	77.0
Nunavut	5,029	1,056	23,885	0.0	0.0	0.0
Ontario	5,853,788	1,233,240	21,569,534	6.6	1.4	24.5
Prince Edward Island	178,185	29,475	221,143	31.1	5.1	38.6
Quebec	6,984,261	1,470,985	18,471,946	5.6	1.2	14.9
Saskatchewan	1,907,723	365,110	7,501,080	3.3	0.6	13.1
Yukon Territory	294,795	224,353	3,112,059	0.7	0.5	7.0
Canada	**32,270,485**	**10,530,326**	**109,793,700**	**3.8**	**1.3**	**13.0**

3.2.2 *Interface by Homogenous Fire Regime zone*

Interface areas are not constrained to political boundaries, so Homogenous Fire Regime zones (HFR) are used here to produce an alternate set of interface area data. Data are presented as choropleth maps (Figure 3-6; where features are colour-coded to indicate their value) to show the spatial location of the zones along with the amount of interface area (as opposed to the table for the provincial/territorial areas in Table 3-2). HFR zones are areas of similar fire regimes, with "fire regimes" being characteristics such as how much area burned is by human or natural causes, number of fires, how frequently an area burns, and seasonality of fires (Boulanger *et al.* 2012). HFR zones were originally created by Boulanger *et al.* (2012), and the HFR zones used here were modified slightly from the original zones from that study. Modifications included adding three zones that were left out of the original zonation because of limited fire activity (i.e. Prairies, Southern Ontario/St. Lawrence, and North), thus permitting full coverage of Canada with HFR zones for analysis purposes. The second modification involved splitting the Eastern Temperate zone into east and west portions, reflecting a more accurate depiction of climate, policies, and interface patterns in the two areas (Stocks *et al.* 2002).

Figure 3-6 displays six choropleth maps for each of the three interface types by total area and as a percentage of total land area for each HFR zone. Looking at Figure 3-6a, the HFR zones with the largest area of WUI are the Eastern Temperate – East (ET-E) and Eastern Temperate – West (ET-W) with 5.8 and 5.5 million ha of WUI, respectively. WUI as a percentage of HFR zone land area is highest in ET-E at 39.6%, followed by Southern Ontario/St. Lawrence (SOSL) at 19.8%, ET-W at 14.9%, and Southern Cordillera (SC) at 11.5% (Figure 3-6b).

The largest area of WII is found in the Southern Prairies (SP) zone with 1.9 million ha, followed by SC at 1.8 million ha (Figure 3-6c). By percentage of land area, ET-E is the highest at 7.9%, followed by SC at 5.4% (Figure 3-6d).

For infrastructure interface, ET-W dominates in area at 19.6 million ha, followed by SP at 14.4 million ha and SC at 13.2 million ha (Figure 3-6e). By percentage of land area, ET-E again dominates with 68.1% of its land area being infrastructure interface, followed by ET-W at 50.2%, and SC at 40.5% (Figure 3-6f).

Figure 3-6. Fire regime zone choropleth maps for three interface types (by area, %).
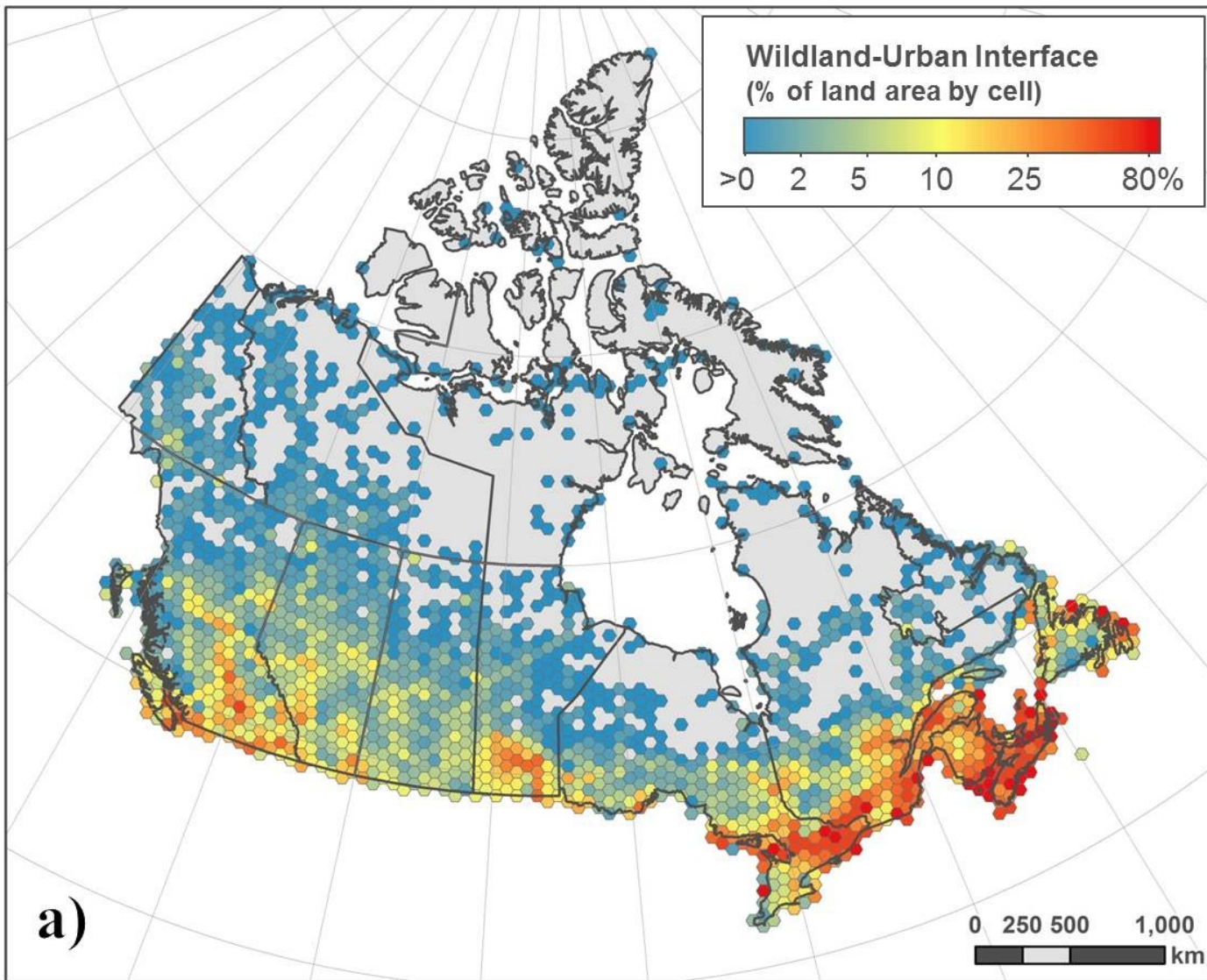Choropleth maps of interface in Canada by Homogenous Fire Regime zones (HFR zones), with **a)** wildland-urban interface (WUI) area (million hectares) in each HFR, **b)** WUI as a percentage of HFR zone land area (%), **c)** wildland-industrial interface (WII) area (million hectares) in each HFR zone, **d)** WII as a percentage of HFR zone land area (%), **e)** infrastructure interface area (million hectares) in each HFR zone, **f)** infrastructure interface as a percentage of HFR zone land area (%). HFR zone names on maps are: Eastern Subarctic (ES), Great Slave Lake (GSL), Southern Cordillera (SC), Lake Winnipeg (LW), Eastern Temperate – East (ET-E), Eastern Temperate – West (ET-W), Lake Athabasca (LA), Eastern James Bay (EJB), Interior Cordillera (IC), Western Ontario (WO), Western Subarctic (WS), Great Bear Lake (GBL), Western James Bay (WJB), Southwestern Yukon (SY), North Atlantic (NA), Southern Prairies (SP), Pacific (P), Prairies (PR), Southern Ontario/St. Lawrence (SOSL), North (N).

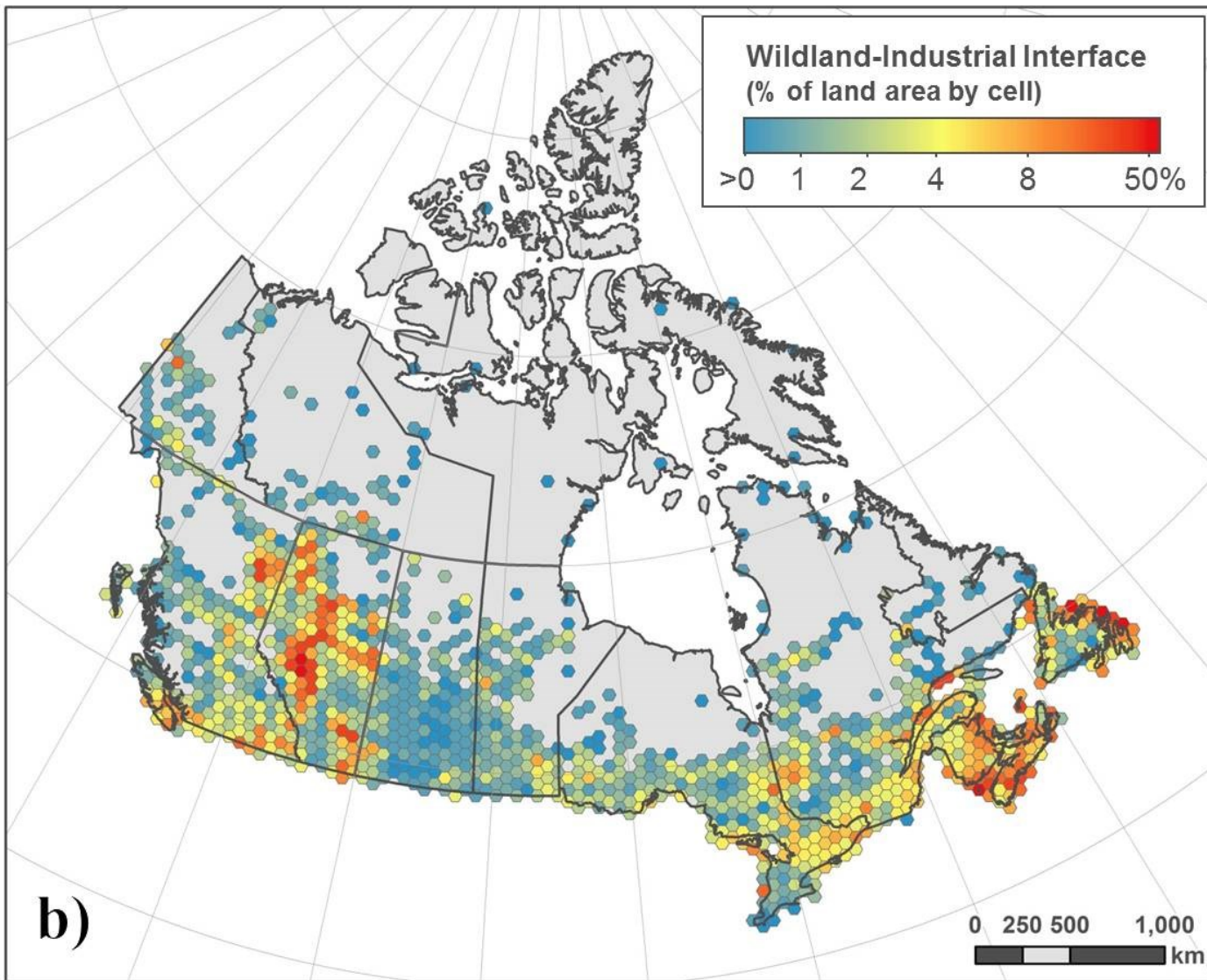### 3.2.3 National Interface Landscape Metrics

To investigate the spatial patterns of interface, the fine scale interface rasters were downgraded or "binned" into a grid of hexagonal cells. Hexagonal binning or using hexagon-shaped grid cells to represent data is not a new technique, but recently is increasingly popular for displaying and analysing data. There are two main reasons behind using hexagonal cells over rectangular cells; first, the hexagonal cells display data in a much more visually appealing manner, and second, the hexagonal cells are more appropriate for accurate data representation from a mathematical perspective. The characteristics responsible for the improved accuracy include: 1) minimized edge effects by having a lower perimeter to area ratio than rectangular cells, 2) data near the edges of a hexagonal cell have a more consistent distance to cell centroid (e.g. compare to the far corners of a square cell), 3) between each cell, the distance to the next centroid is constant, and each cell has six identical neighbours each sharing one side (vs. square cells with four side neighbours and four diagonal neighbours sharing a vertex), and 4) due to their shape, hexagonal cells fit to a curved surface when working at larger scales (Birch *et al.* 2007). One notable limitation of using aggregated data is that the scale to which the data is aggregated will affect the results. For example, data aggregated to ~1 degree cells will look different than data aggregated into much larger or much smaller cells. Cell size here (~1 degree) was chosen to reflect a balance between appropriate scale for analysis, data processing and display, and the practical applications of this analysis.

Figure 3-7a-c shows the WUI, WII, and infrastructure interface areas aggregated into a grid of hexagonal cells. The hexagonal grid was created using the "Repeating Shapes" tool (v. 1.5.152) for ArcGIS (Jenness 2012). Each hexagonal cell is approximately 1 degree by 1 degree (exact cell area is 3400 km^2, which is ~1 degree by 1 degree at mid-latitudes of Canada). Interface areas were aggregated into the hexagonal cells and are represented as a total interface area as a percent of total land area in each cell (all non-water area within Canada's borders was included as land area).
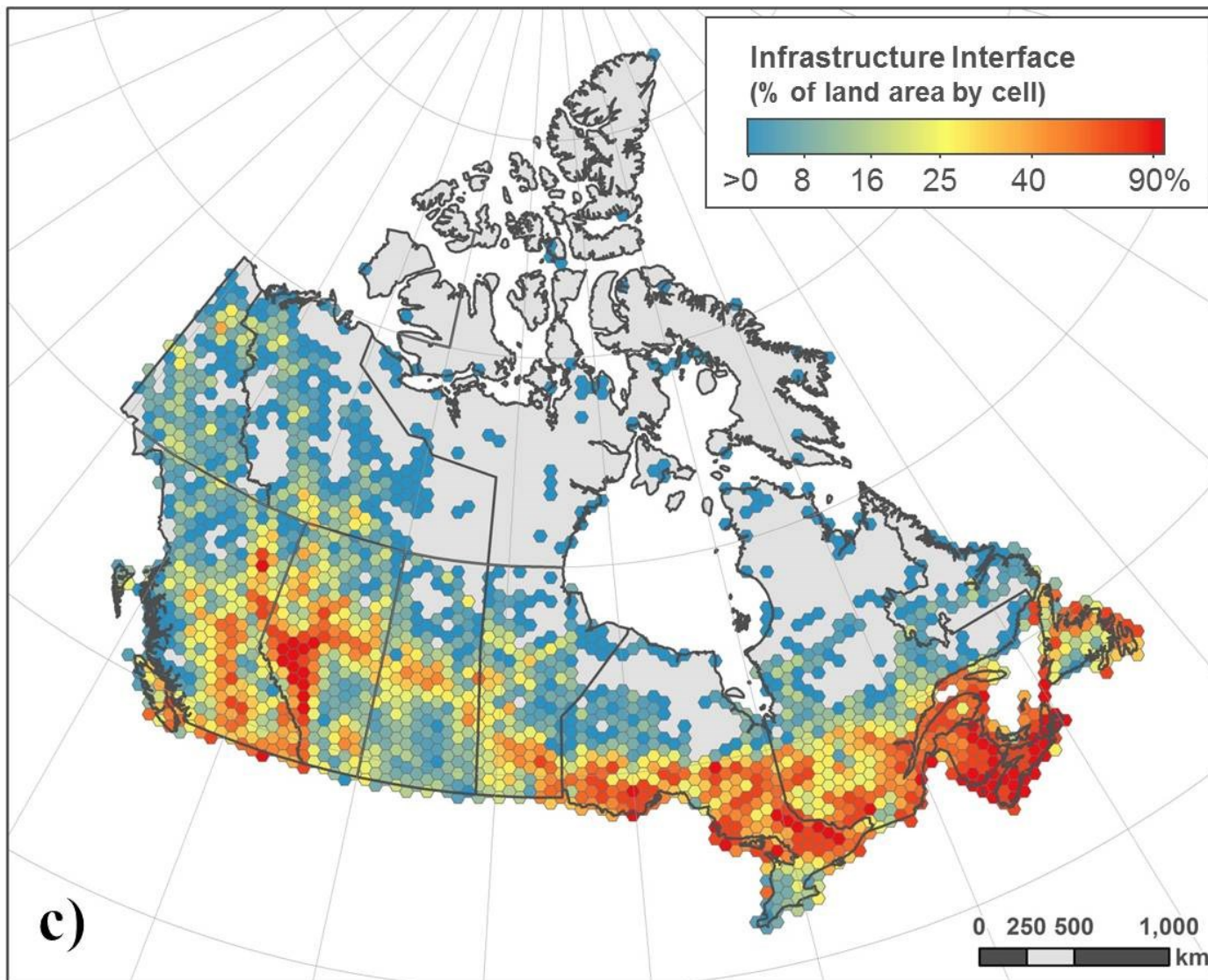
For WUI, Figure 3-7a shows spatial clustering of interface areas in the southern portion of the country. Eastern Canada has more high density cells than central and western Canada. Figure 3-7b shows a similar southern concentration of interface areas WII as was seen for WUI. Eastern Canada also has some areas of higher density WII. However, unlike the WUI, the WII shows a large area of high densities within Alberta. Figure 3-7c shows a similar southern concentration of infrastructure interface, but with a more widespread distribution of high density cells.

Legend (within figure):
Wildland-Urban Interface
(% of land area by cell)

>0 2 5 10 25 80%

a)

0 250 500 1,000
km

(Figure 3-7 continues on next page)

(Figure 3-7 continues on next page)

Figure 3-7. Density of interface by hexagonal cells.
Density (percent of land area in each hexagonal cell) of national interface area within hexagonal ~1 degree cells (exact cell area is 3400 km^2, which is ~1 degree by 1 degree at mid-latitudes of Canada) for **a)** wildland-urban interface, **b)** wildland-industrial interface, and **c)** infrastructure interface.

In order to quantitatively assess the spatial clustering of the interface hexagonal cells, tests for spatial autocorrelation were performed. On a national scale, Global Moran's I tests (Moran 1950) were performed on each of the three grids to detect the presence of spatial autocorrelation (using the "Spatial Autocorrelation (Moran's I)" Spatial Statistics tool for ArcGIS). Results of the tests indicate that all three interface types do show spatial autocorrelation (Moran's Index = 0.71, 0.57, and 0.82 for WUI, WII, and infrastructure interface, respectively) and follow a statistically significant clustered pattern (for WUI, WII, and infrastructure interface, respectively: z-score = 119.96, 96.65, 137.79 and p-value < 0.0001).

To assess spatial clustering at a smaller scale, the Anselin Local Moran's I statistic (Anselin 1995) was determined for each hexagonal cell for the three interface maps Figure 3-8a-c (using the "Cluster and Outlier Analysis (Anselin Local Moran's I)" Spatial Statistics tool for ArcGIS). With the Local Moran's I, "clusters" are cells with a positive value for the Anselin Local Moran's I statistic. Furthermore, clusters of high values also have a positive z-score and a significant p-value, and clusters of low values have a negative z-score and a significant p-value. All significant clusters in this analysis were clusters of high values (for WUI: Anselin Local Moran's I = 4.80 to 836.65, mean Anselin Local Moran's I = 72.64, z-score = 1.96 to 342.68, mean z-score = 29.75, p-value = 0 to 0.049, mean p-value = 0.002; for WII: Anselin Local Moran's I = 4.76 to 2619.66, mean Anselin Local Moran's I = 70.39, z-score = 1.97 to 1082.88, mean z-score = 29.10, p-value = 0 to 0.049, mean p-value = 0.002; for infrastructure interface: Anselin Local Moran's I = 4.81 to 366.98, mean Anselin Local Moran's I = 51.39, z-score = 1.97 to 150.02, mean z-score = 21.01, p-value = 0 to 0.049, mean p-value = 0.002). The Anselin Local Moran's I test also can detect spatial outliers (e.g. where a cell with a high value is surrounded by cells with much lower values); no outliers were detected in any of the three interface hexagonal grids.

## 3.3   Fuels, Structures, and Interface

Interface maps in this study were produced using the two components that form interface areas: wildland fuels and human-built structures. For an area to be defined as an interface area, it is required that wildland fuels are 2400 m or less (depending on fuel cover type and arrangement) from a structure; both fuel and structure features must be present for an area to be interface (as discussed in section 2.2). Since fuels and structures were the input that went into
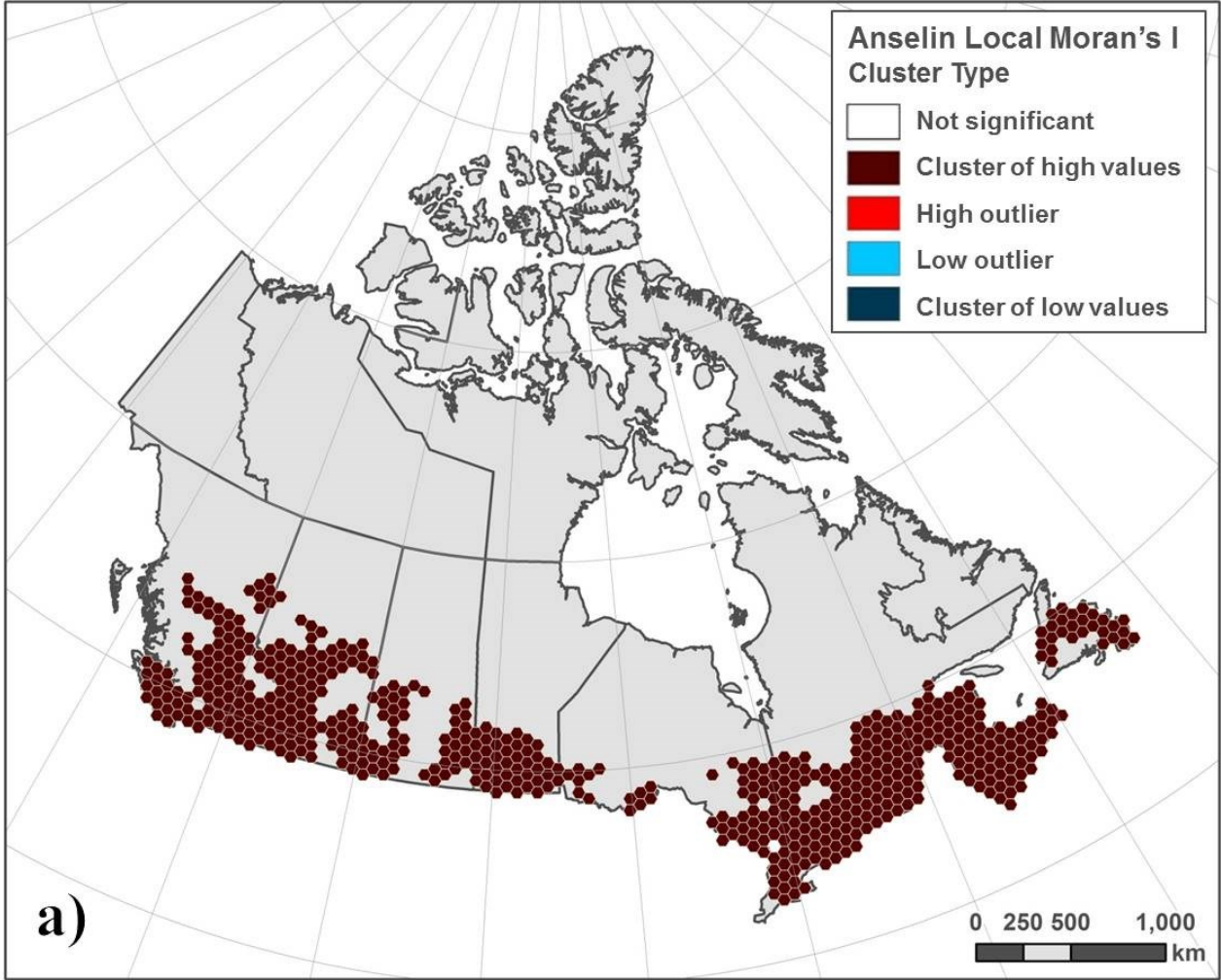
(Figure 3-8 continues on next page)
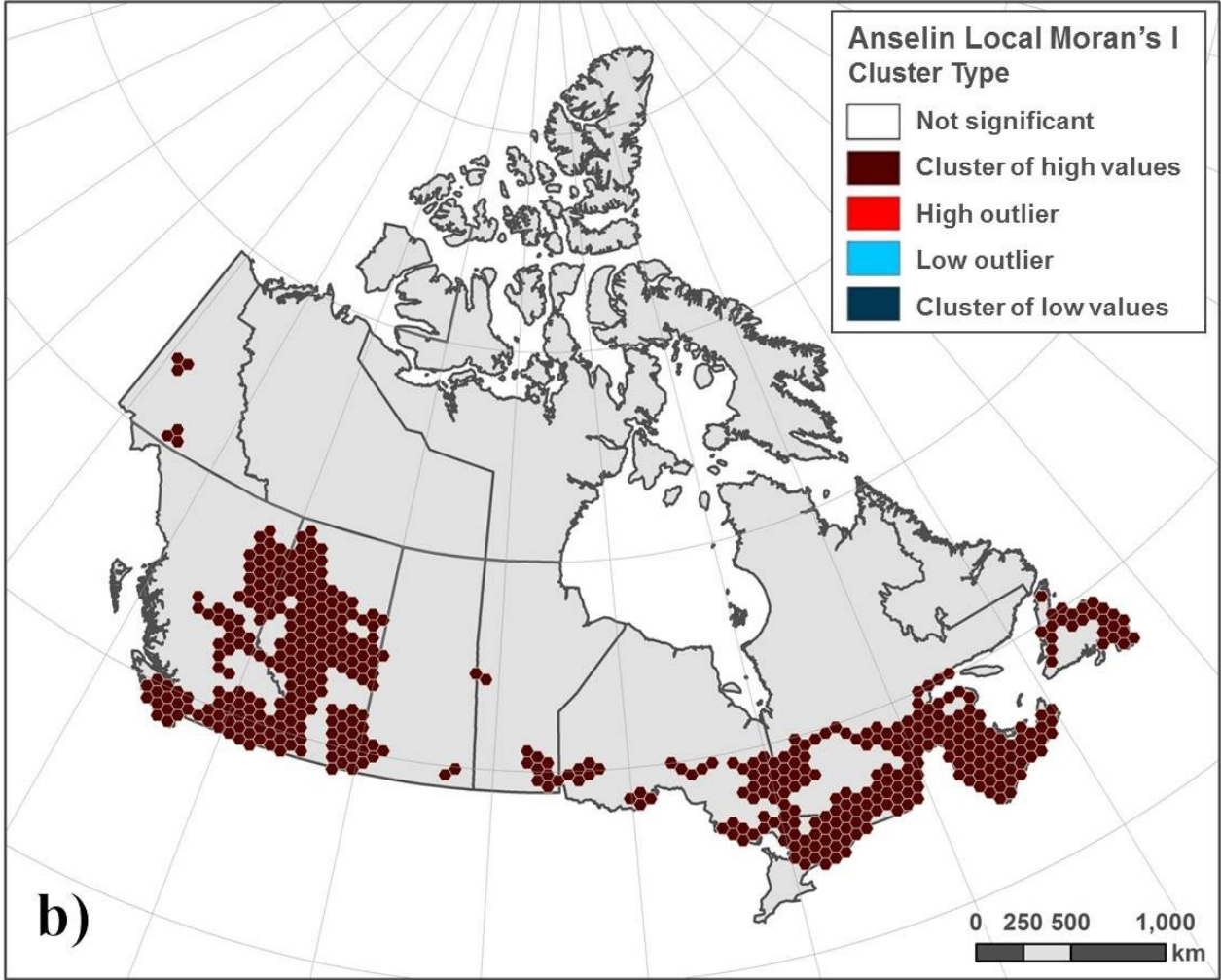
(Figure 3-8 continues on next page)
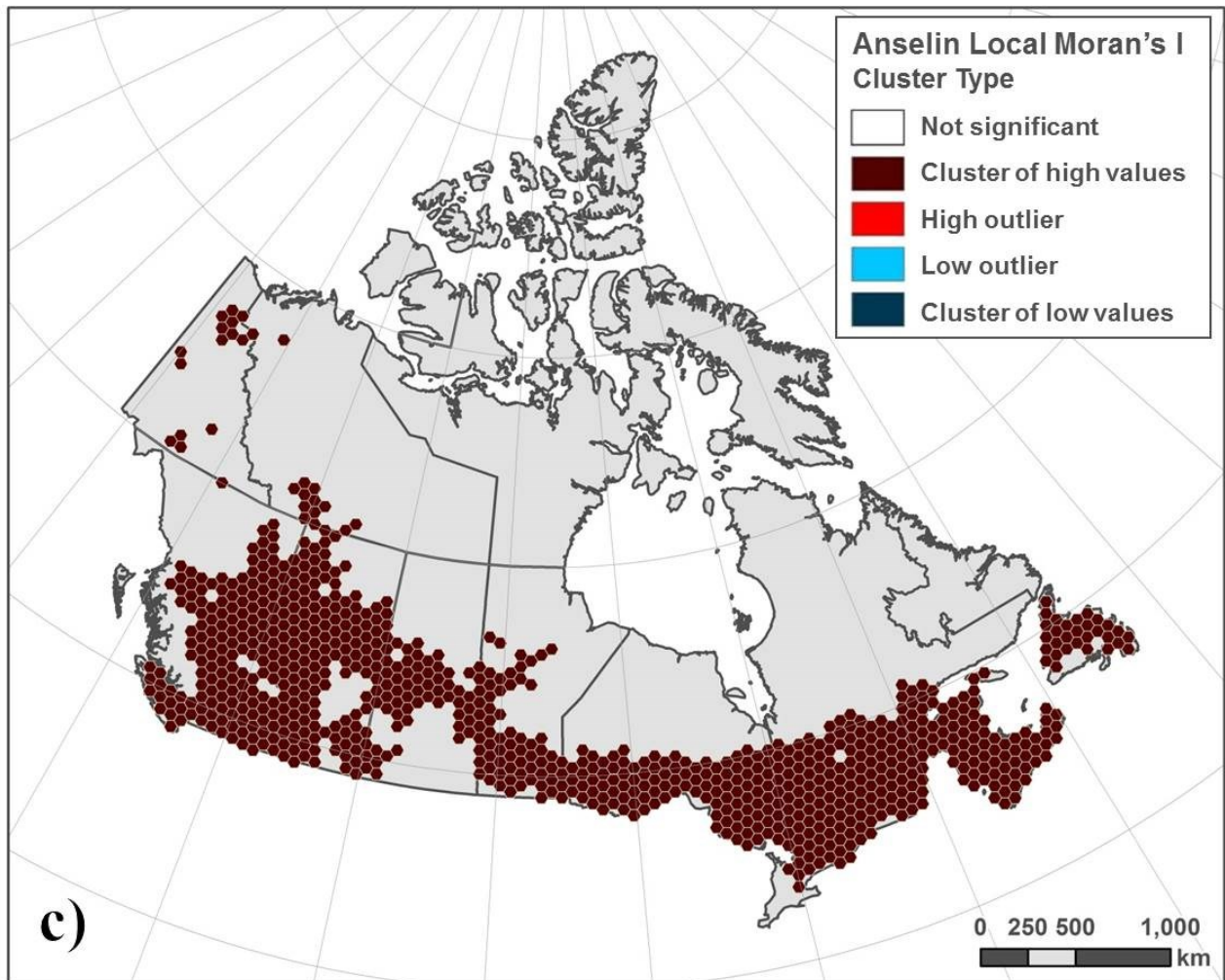
Figure 3-8. Anselin Local Moran's I cluster type by hexagonal cell.
Map of Anselin Local Moran's I cluster type (cluster of high values/cluster of low values/high outlier/low outlier) produced from the analysis of hexagonal cells (interface area per cell) for **a)** wildland-urban interface, **b)** wildland-industrial interface, and **c)** infrastructure interface. Cells depicted are hexagonal ~1 degree cells (exact cell area is 3400 km^2, which is ~1 degree by 1 degree at mid-latitudes of Canada).

creating the interface maps, statistical spatial analysis of the relationship is not rational. However, to give an idea of the relationships between fuels, structures, and interface, visual examination of the three variables can be performed.

To investigate the relationship between fuels, structures, and interface on a coarse scale, data were summarized by the same ~1 degree hexagonal cells described in section 1.1.1. Figure 3-9 shows scatterplots of the cell summary data with all three variables. For the three interface types (WUI, WII, and infrastructure interface: Figure 3-9a-c), there are many data points with very low structure density (~0%) but a wide variety of fuel densities (~0 to 100%). For the WUI and infrastructure interface (Figure 3-9a and c), there is a strong trend of increasing interface

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density with increasing fuel density, and to a lesser degree the same trend can be seen with increasing interface density with increasing structure density. For WUI, the maximum WUI densities are generally seen in cells where there is ~80 to 90% fuel density and ~1 to 3% structure density (Figure 3-9a). For infrastructure interface, the maximum densities are generally seen in cells where there is ~80 to 98% fuel density and ~2 to 7% infrastructure values (i.e. structure) density (Figure 3-9c). For the WII (Figure 3-9b), trends are not as clear; density of WII does appear to increase slightly with fuel density, and only a very subtle increase with lower values of structure density.

To investigate these relationships from a spatial perspective, national maps of the hexagonal cell summary data were categorized according to levels of interface, fuels, and structures (Figure 3-10). For each map, cells with no interface area are removed entirely, and cells with "low" interface densities are shown in black ("low" is classified as hexagonal cells with ≤ 1% WUI, ≤ 0.5% WII, or ≤ 7% infrastructure interface as a percent of the cell land area; these values represent thresholds for approximately the lowest 1/3 of the data). For all other interface values (i.e. "med-high", or above the "low" thresholds), cells are classified by fuel and structure categories: low fuels with high structures, high fuels with high structures, and high fuels with low structures. At this scale, the category that reflects the highest potential risk is the high fuels with high structure density. This high/high category is seen mostly in areas where interface density is also high (compare to Figure 3-7). Specific areas with the high/high category include: the southern portion of the country, southeastern Canada, and the border between the prairies and the boreal forest. Infrastructure interface (Figure 3-10c) does have a much broader extent of the high/high category. For all three maps (WUI, WII, and infrastructure interface), southern Ontario and the prairies largely have the low fuel with high structure category.
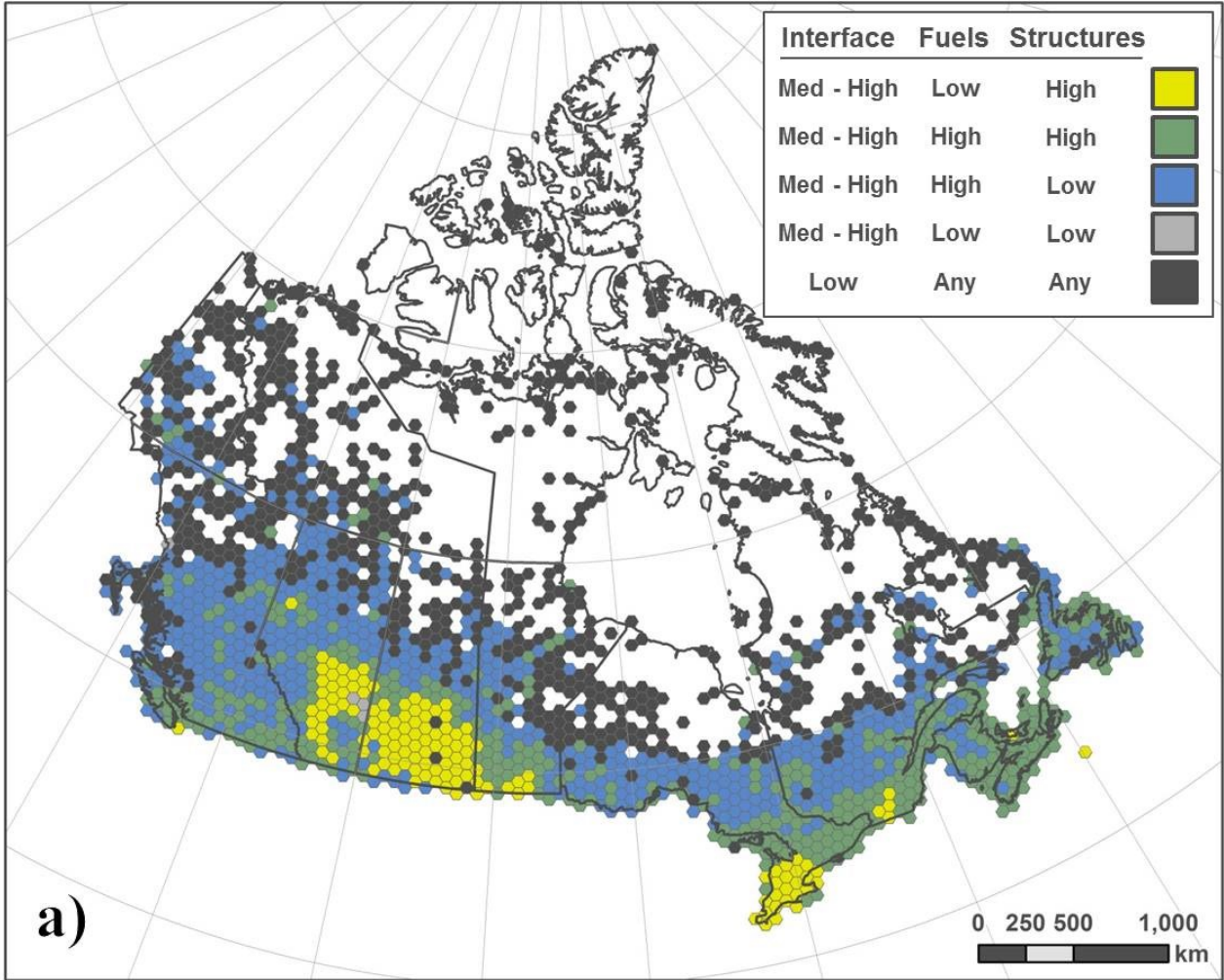
3.3.1 *Fuels and Interface*

The characteristics of wildland fuels and the relationship with interface areas in this study are presented in this section. Nationally, there are 562 million ha of wildland fuels in Canada, covering 67% of the total land area of Canada. Fuels by "fuel weight" (where 1 is the highest hazard and 7 is the lowest hazard; section 2.3.1) are shown in Figure 3-11. The majority (80%) of the national fuel area can be considered "high hazard" fuels (i.e. have a relative fuel weight of 1-3 and are considered to have a higher difficulty of suppression).

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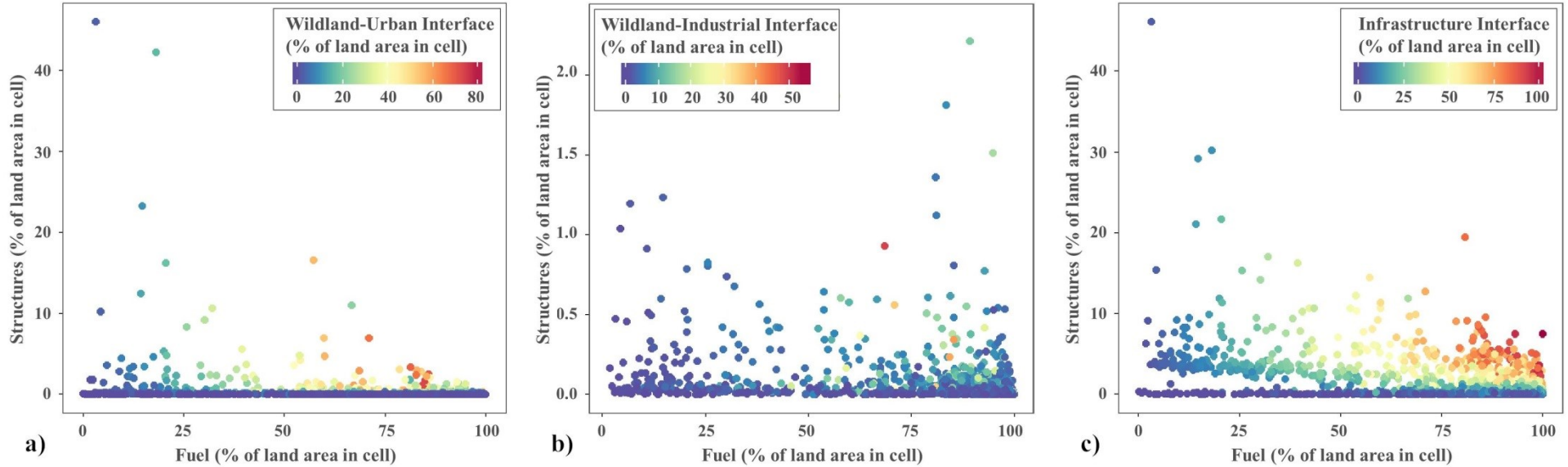
Figure 3-9. Three-way graphs of structures, fuels, and interface.
Data are summarized by "cell", where the cells are the same hexagonal ~1 degree cells (exact cell area is 3400 km², which is ~1 degree by 1 degree at mid-latitudes of Canada) used previously (discussed in section 1.1.1). Graphs show fuel (as % of land area within cell) by **a)** urban structures (as % of land area within cell) with wildland-urban interface (as % of land area within cell) shown in colour scale depicted in the legend, or **b)** industrial structures (as % of land area within cell) with wildland-industrial interface (as % of land area within cell) shown in colour scale depicted in the legend, or **c)** infrastructure structures (or more accurately, "values"; as % of land area within cell) with infrastructure interface (as % of land area within cell) shown in colour scale depicted in the legend. Cells with no interface are not shown; cells with very low amounts of interface are shown (i.e. 0.0001%).
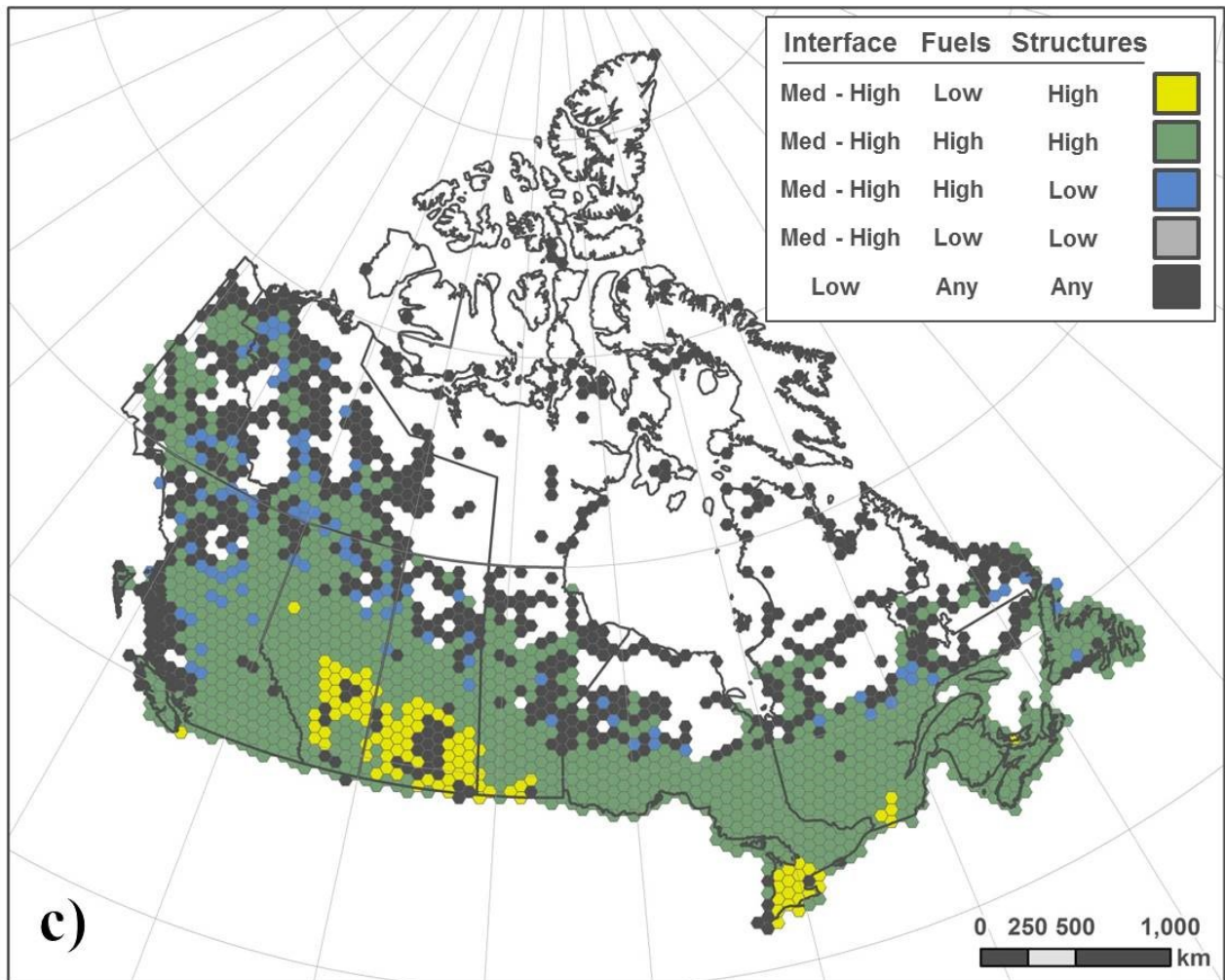
(Figure 3-10 continues on next page)
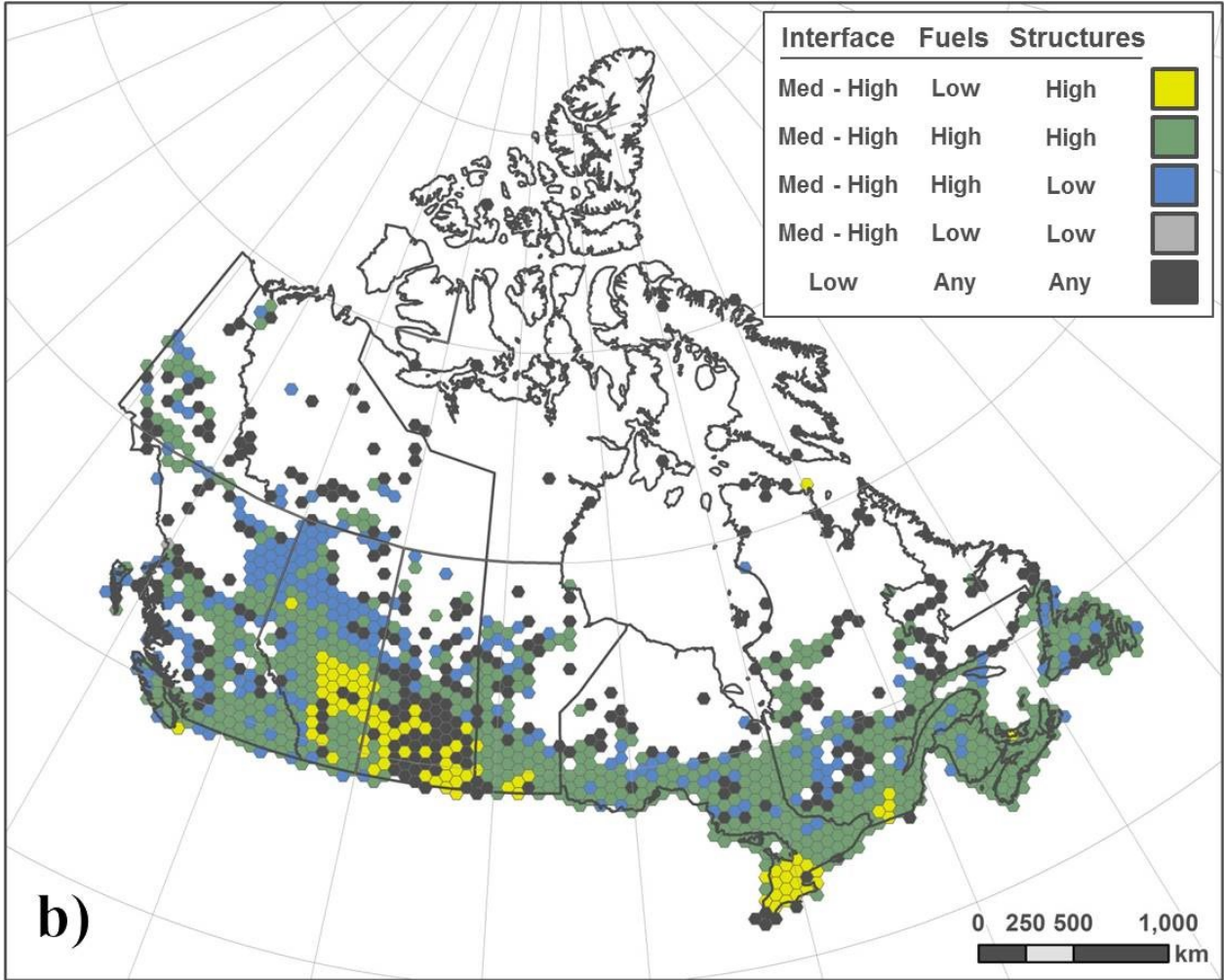
(Figure 3-10 continues on next page)

Figure 3-10. Three-way categorical maps of interface, fuels, and structures.
Combined categories of densities (percent of land area in each hexagonal cell) for interface, fuels, and structures within hexagonal ~1 degree cells (exact cell area is 3400 km^2, which is ~1 degree by 1 degree at mid-latitudes of Canada). Cells with no interface are not shown. Cells with low amounts of interface are shown in black when interface densities are less than: **a)** 1% of land area within a cell mapped as wildland-urban interface (WUI), **b)** 0.5% of land area within a cell mapped as wildland-industrial interface (WII), and **c)** 7% of land area within a cell mapped as infrastructure interface. Above these thresholds, cells are classified according to fuel and structure density: "high" fuel density is shown in blue (> 30% of land area), "high" density of structures is shown in yellow (> 0.06% for WUI structures (a), > 0.009% for WII structures (b), or 0.09% for infrastructure values (c)), and "high" densities of both fuels and structures is shown in green.

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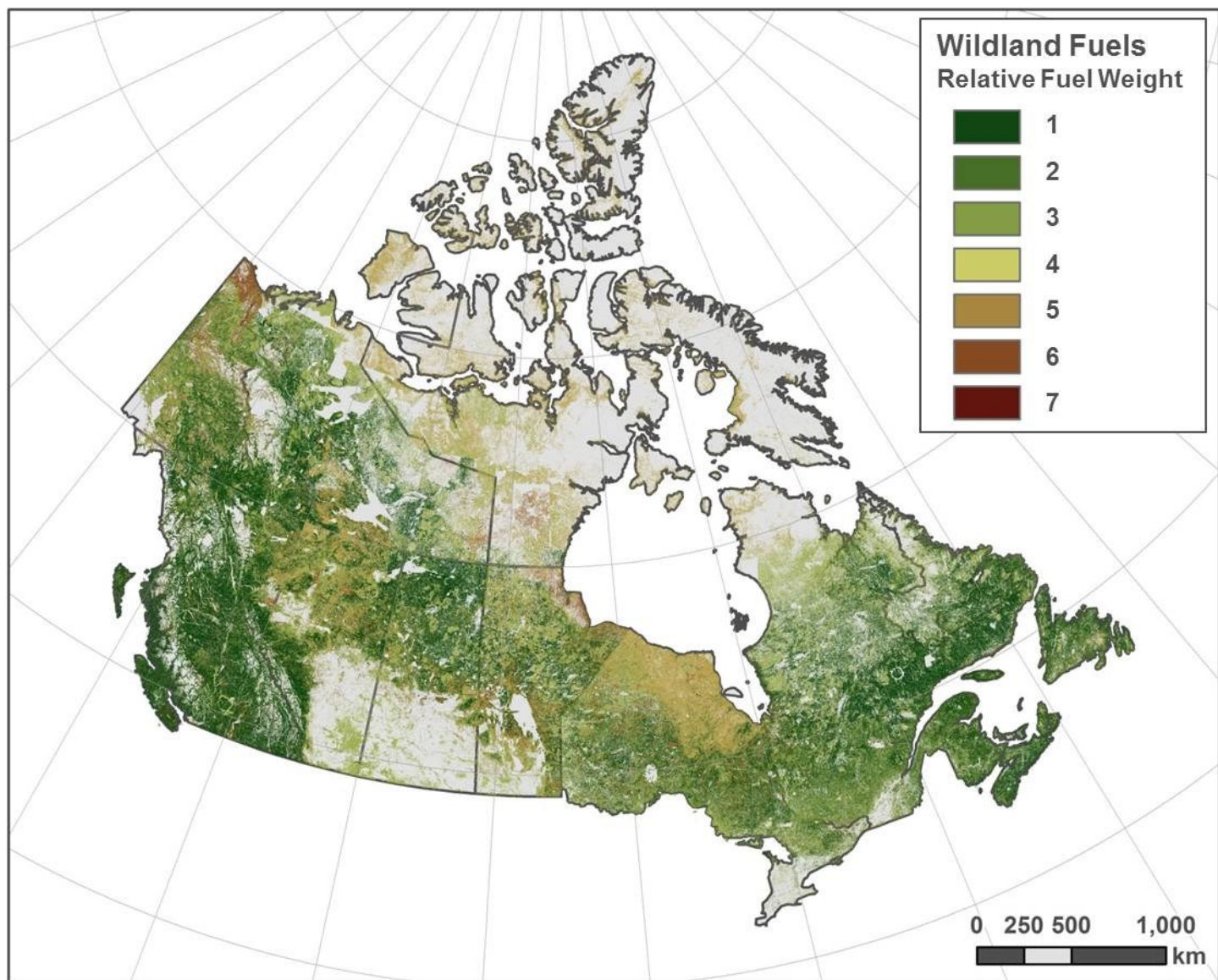
Figure 3-11. National fuel raster.
Fuel raster of national wildland fuels, showing rankings from 1-7 (where 1 is higher potential hazard, 7 is lower) as described in section 2.3.1.

As mentioned previously (section 3.1), 20.7% of wildland fuels are classified as wildland-human interface (Table 3-1). Specifically, 5.8% of fuel area is classified as WUI, 1.9% as WII, and 19.5% as infrastructure interface (with significant overlap between the three interface types).

To investigate the spatial relationships between density of fuels and density of interface areas, the same hexagonal grid that was used as in section 1.1.1 for a visual analysis. Within each hexagonal cell, categories (high/medium/low) of the density of fuels (fuel area as a percentage of land area in each cell) were crossed with categories (high/medium/low) of the density of interface (interface area as a percentage of land area in each cell) for each interface type and the resultant nine categories were colour coded; the results are shown in Figure 3-12a-c. Cells with high/high, high/medium, and medium/medium categories (shown in shades of red and orange) are mostly found within the boreal forest and also in the southern portions of the country which are not fuel-limited (i.e. agricultural areas in the prairies and southwestern Ontario, and heavily built-up areas such as southern Ontario).

Further analysis was performed in order to determine if the amount of fuel cover types with "high hazard" differs between areas that are classified as interface or not interface. Randomly sampled points were selected across each province and territory, with the number of random samples proportional to 0.01% of provincial or territorial land area. Using the randomly sampled points, χ^2-tests for equality of proportions were performed for each province or territory (with $\alpha = 0.05$ and $n = 1500$) [8].

Nationally, it was found that there are a higher proportion of "high hazard" fuels within interface areas compared to outside interface areas. For WUI, the proportion inside WUI areas is 93%, and 76% outside (difference of 17%, $\chi^2 = 171$, p-value < 0.0001). For WII, the proportion of "high hazard" fuels inside WII areas is 90%, and 76% outside (difference of 13%, $\chi^2 = 96$, p-value < 0.0001). Infrastructure interface has a proportion of 90% inside and 74% outside (difference of 16%, $\chi^2 = 128$, p-value < 0.0001). Figure 3-13 shows the results for WUI (Figure 3-13a), WII (Figure 3-13b), and infrastructure interface (Figure 3-13c) by province and territory. The majority of provinces and territories follow the national findings, with more "high hazard"
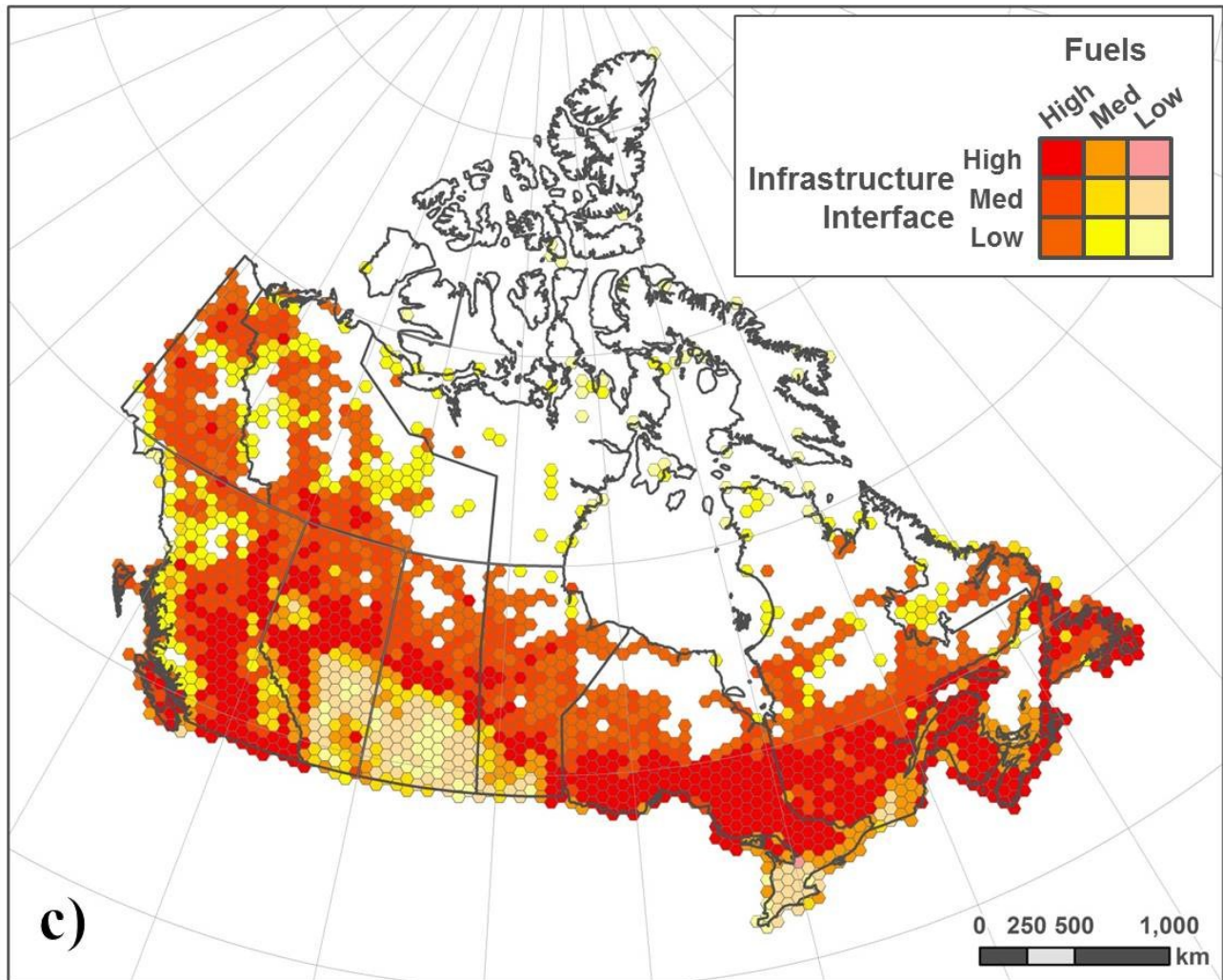
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[8] *Scaled down to n = 1500 from the thousands of sample points per province/territory for a more appropriate sample size for performing statistical tests.*
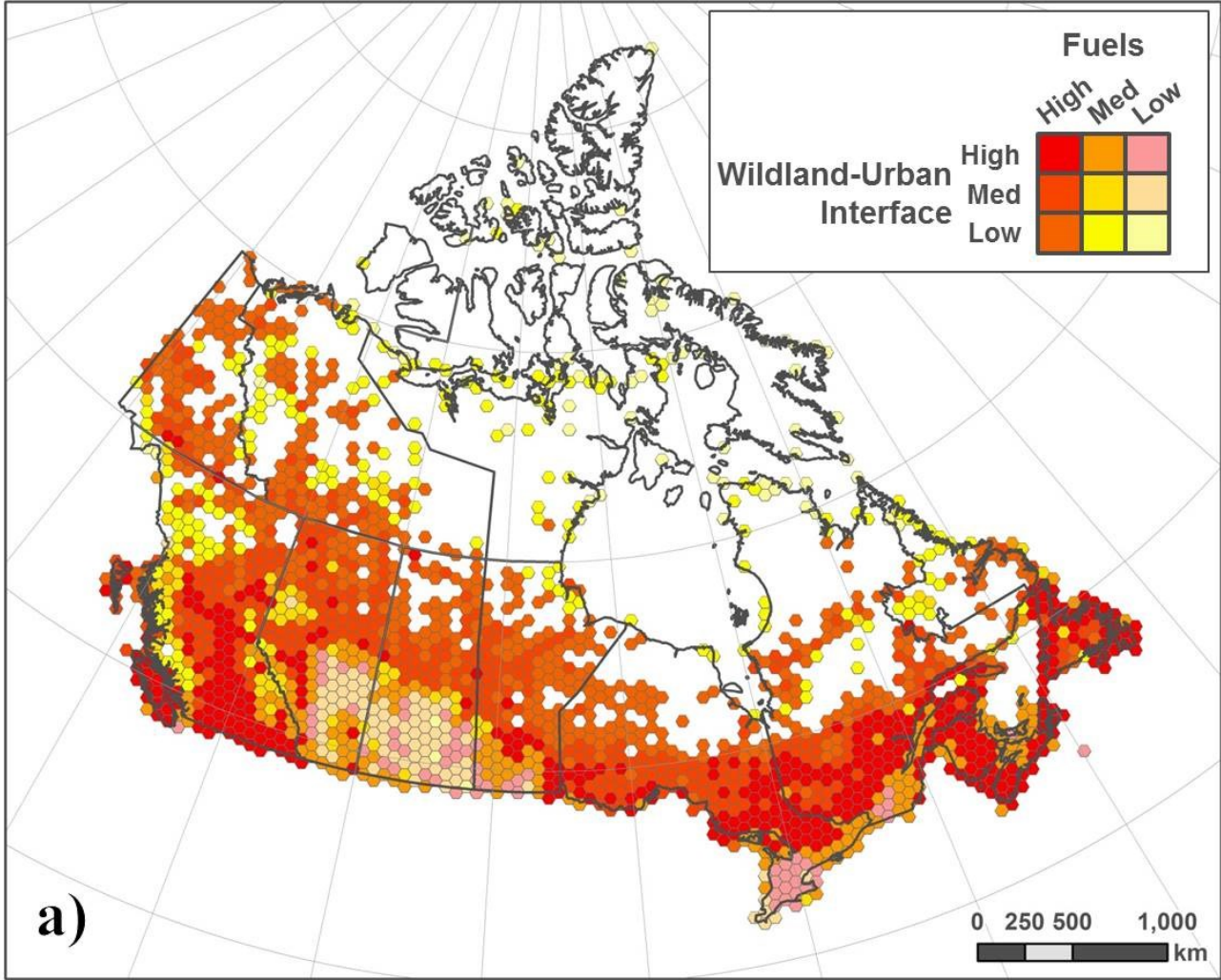
(Figure 3-12 continues on next page)
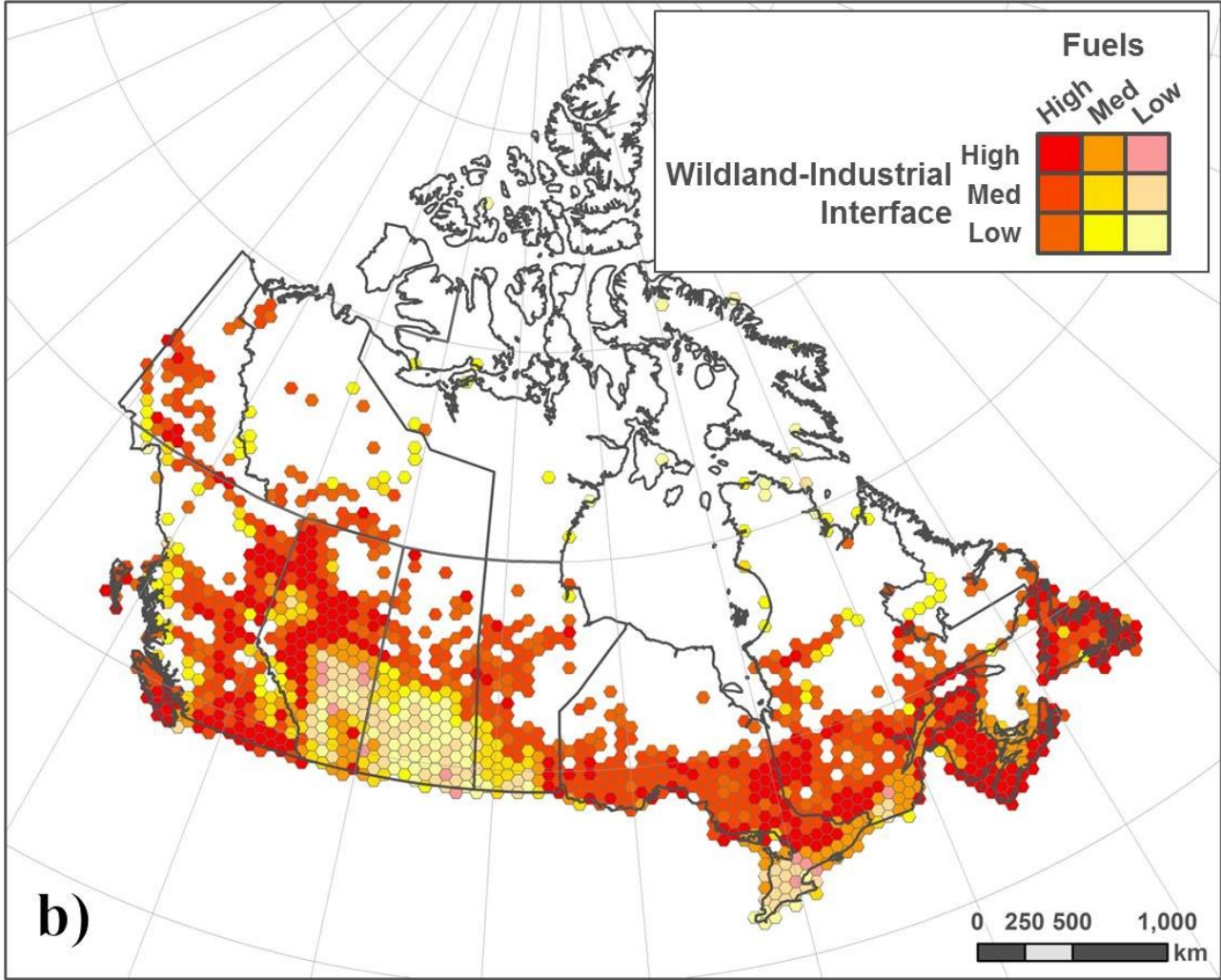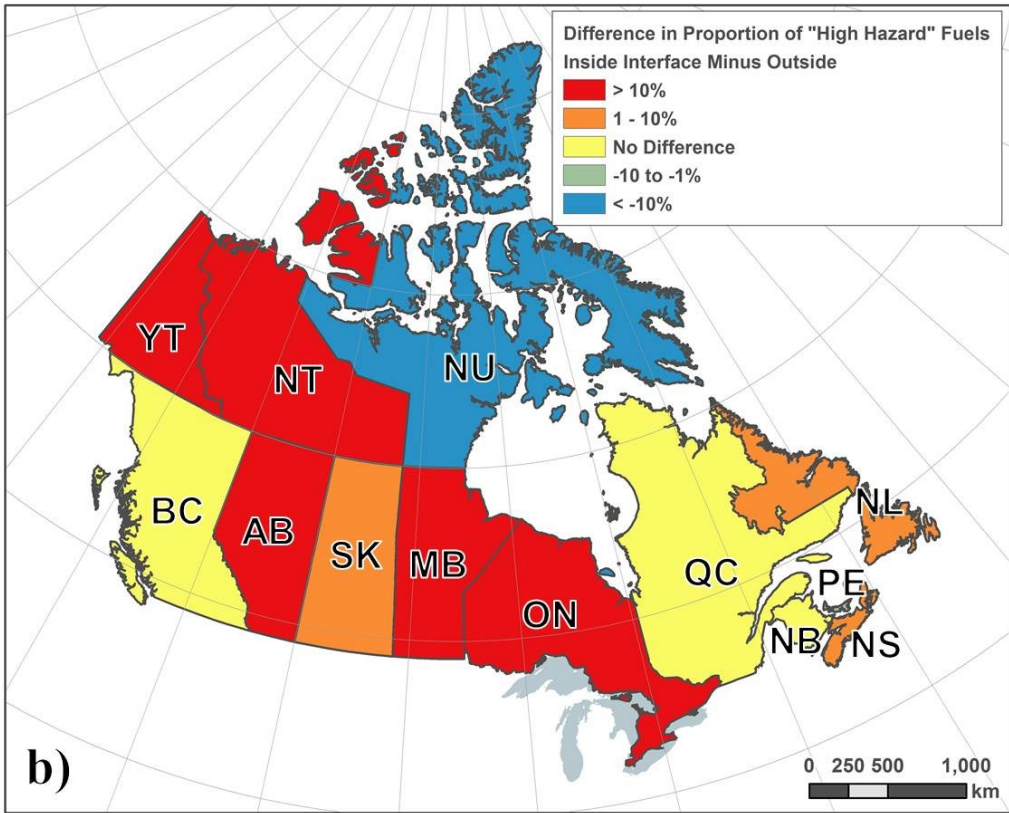
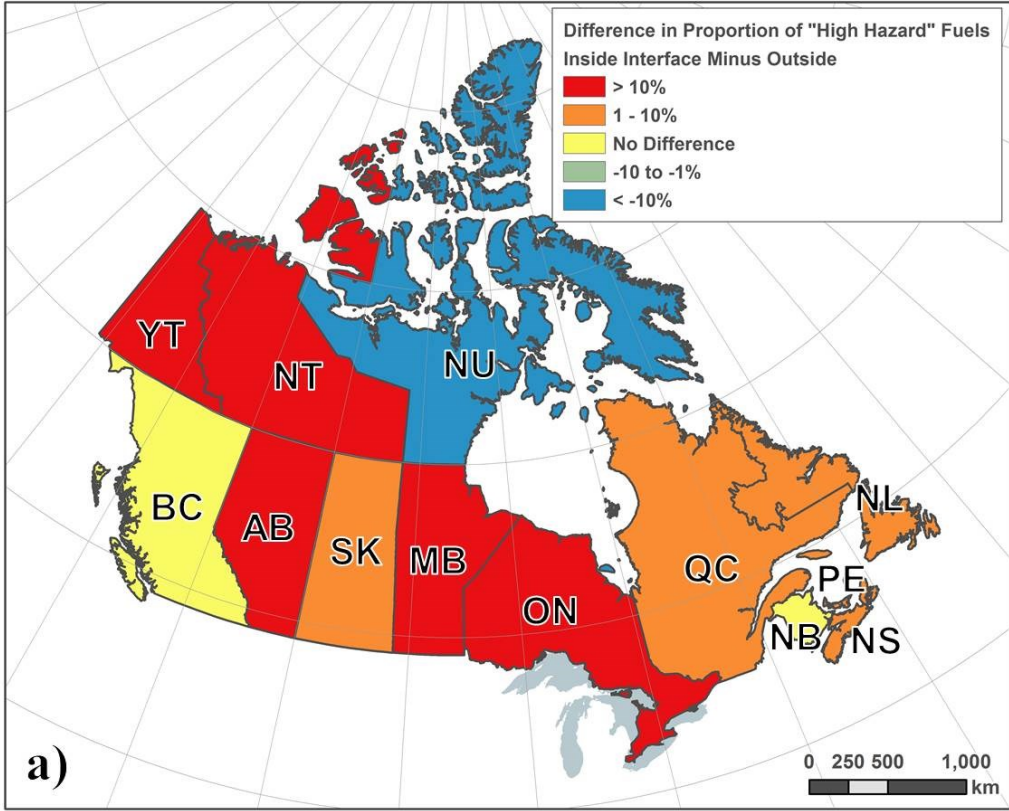*(Figure 3-12 continues on next page)*

Figure 3-12. Categorical national maps of interface areas by wildland fuels.
Categories of fuel density (fuel area as a percent of land area in each hexagonal cell) crossed with categories of interface density (interface area as a percent of land area in each hexagonal cell) within hexagonal ~1 degree cells (exact cell area is 3400 km^2, which is ~1 degree by 1 degree at mid-latitudes of Canada) for **a)** wildland-urban interface (WUI), **b)** wildland-industrial interface (WII), and **c)** infrastructure interface. Categories (as % of cell land area) of fuel density are high (> 80%), medium (> 30 – 80%), low (≤ 30%); categories for WUI are high (> 6%), medium (> 1 – 6%), low (≤ 1%); categories for WII are high (> 3%), medium (> 0.5 – 3%), low(≤ 0.5%); categories for infrastructure interface are high (> 25%), medium (> 7 – 25%), low (≤ 7%).

fuels inside interface areas than outside (ranging from 1% to 33% more; p-value <0.002).

However, some provinces show no significant difference in the amount of "high hazard" fuels inside vs. outside interface areas (p-value > 0.05; shown in yellow as "No Difference" in Figure 3-13). Nunavut shows the opposite trend, with less "high hazard" fuel inside interface areas (for WUI, WII, and infrastructure interface the difference was -24% to -14%; $\chi2$ = 100-411, p-values all < 0.0001). This conflicting result is due to the fact that Nunavut has almost no "high hazard" fuel (only 1% of the land area).

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(Figure 3-13 continues on next page)
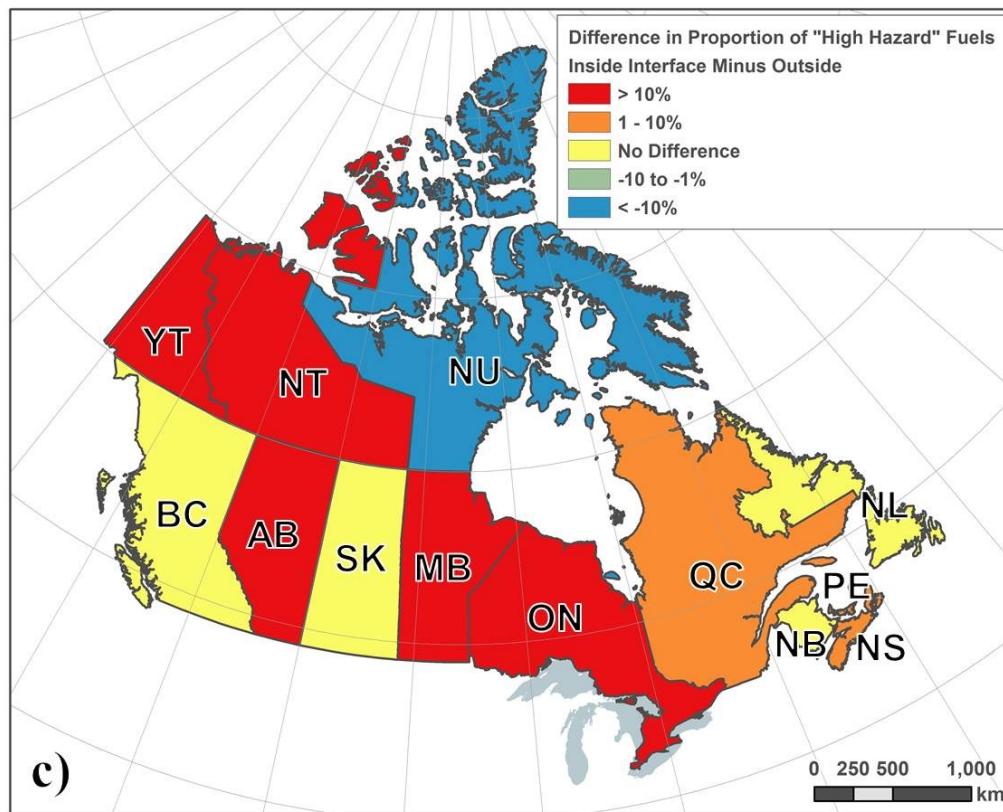
**Figure 3-13. Provincial choropleth maps of difference in proportion of "high hazard" fuel.** Choropleth maps of difference in proportion of "high hazard" fuels inside interface areas compared to outside interface areas by province, where "high hazard" fuels are fuels with a fuel weight of 1-3 (see section 2.3.1) for **a)** wildland-urban interface, **b)** wildland-industrial interface, and **c)** infrastructure interface. Red and orange colours indicate a statistically significant higher proportion of high hazard fuels inside interface areas within a province/territory; green and blue colours indicate a statistically significant lower proportion of high hazard fuels inside interface areas within a province/territory; yellow indicates no statistical difference ($\alpha = 0.05$) in proportion of high hazard fuels inside vs. outside interface areas.

3.3.2 Structures and Interface

Throughout Canada, most structures are found in the southern portion of the country. This configuration is partially responsible (along with wildland fuels) for the pattern of more interface areas being found in these southern areas. To investigate the relationship in the patterns in structure density and interface density, structures were aggregated into the same hexagonal grid as used in section 1.1.1 and section 3.3.1. Figure 3-14 displays a map showing crossed categories of interface and structure within each hexagonal cell. Categories (high/medium/low) of the density of structures (structures as a percentage of land area in each cell) were crossed with categories (high/medium/low) of the density of interface (interface area as a percentage of land area in each cell) for each interface type and the resultant nine categories were colour coded. Structure density was based on the appropriate structure raster produced from the CanVec+ dataset for the WUI, WII,

and infrastructure interface, as outlined in Table 2-1. For the infrastructure interface, "structures" may not be the best term to use since the majority of the infrastructure "structure" elements are actually not structures, but linear features such as railways, powerlines, and roads; therefore the more general term infrastructure "values" will be used. High densities of structures or values with high densities of interface for both WUI and infrastructure interface are most prevalent in the southern portion of the country (Figure 3-14a and c). High densities of structures coinciding with high densities of WII are much more dispersed across Canada, though there are still higher concentrations of the high categories in central Alberta, southern Ontario, southern Quebec, and some of the east coast provinces (Figure 3-14b).
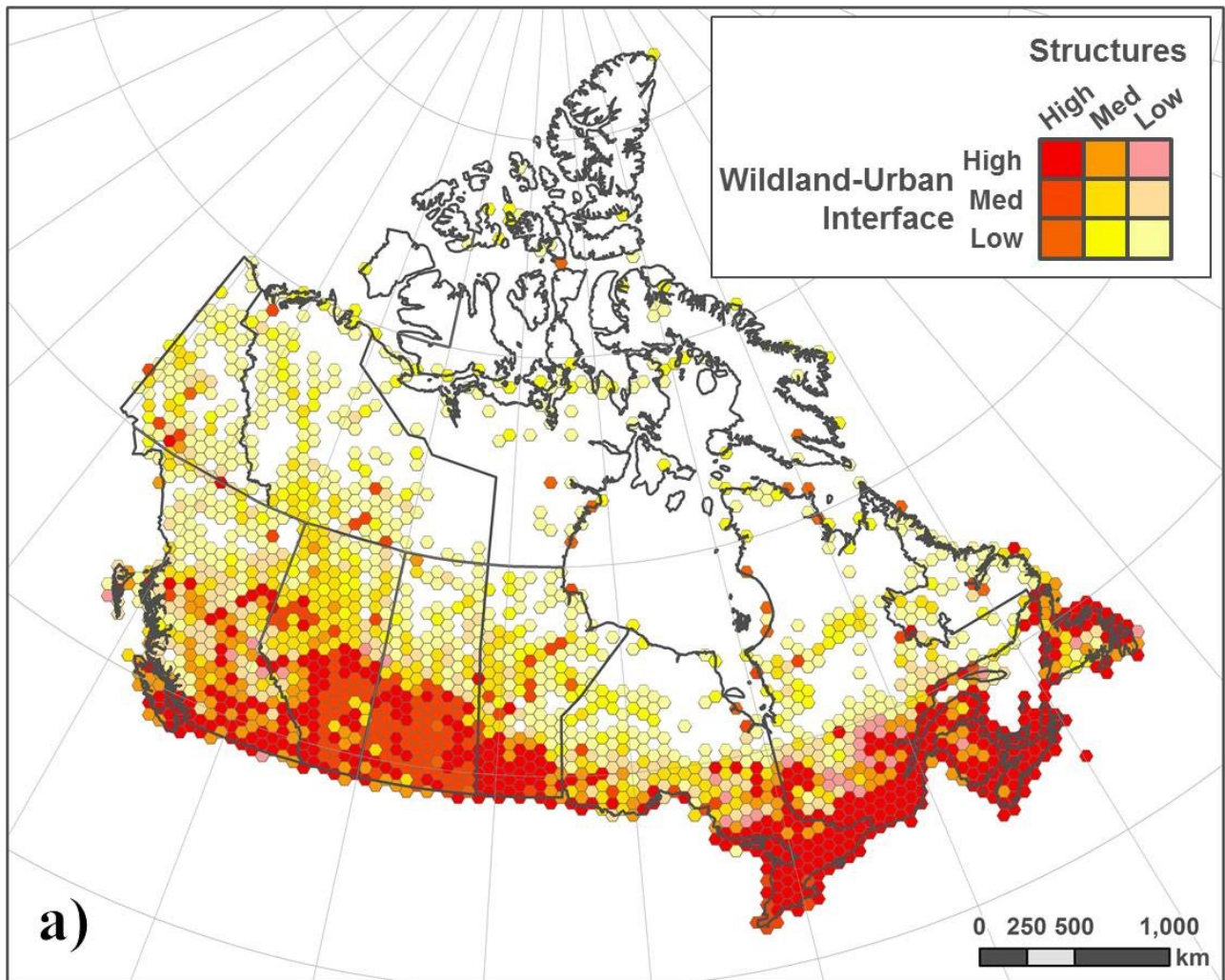
(Figure 3-14 continues on next page)
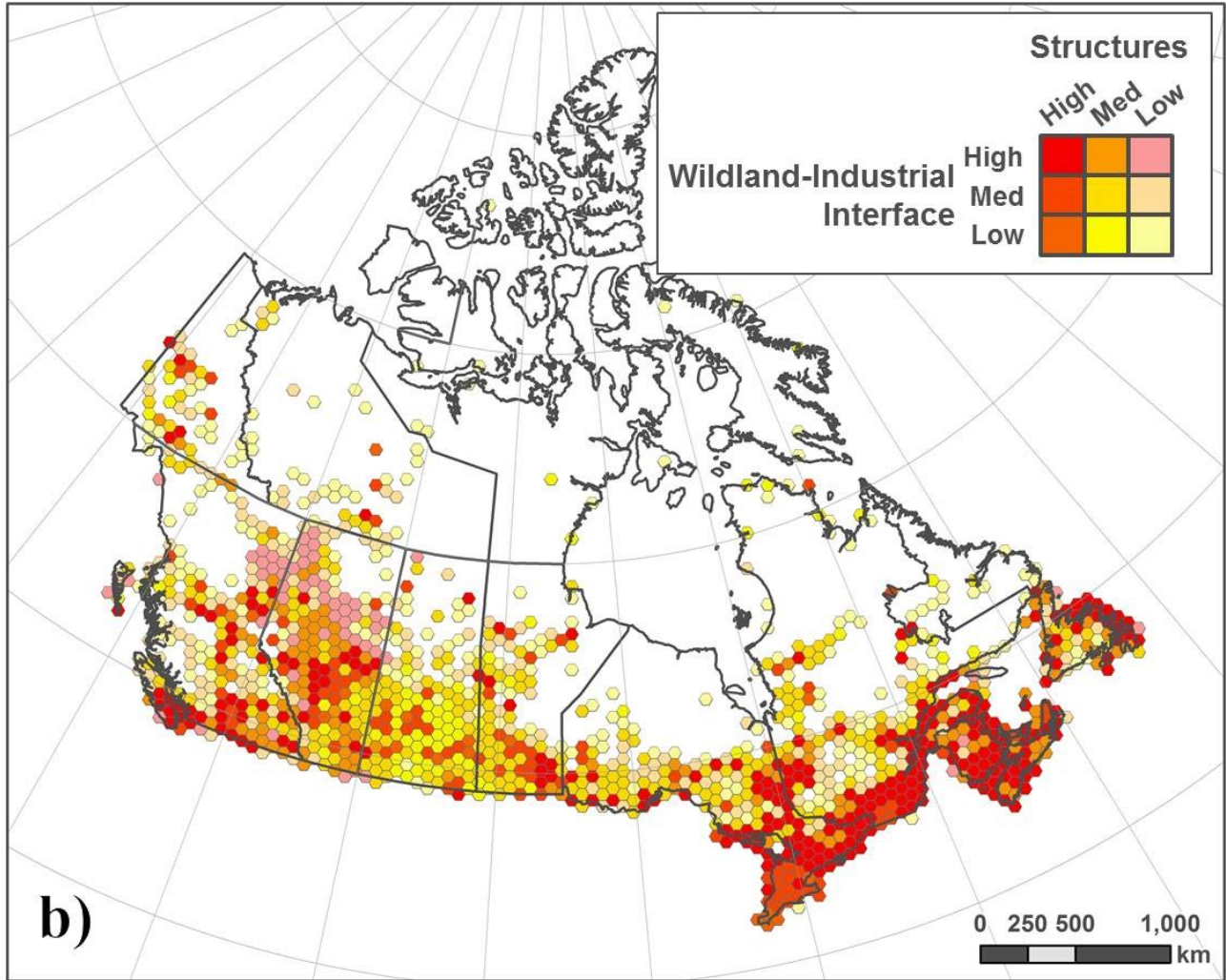
*(Figure 3-14 continues on next page)*
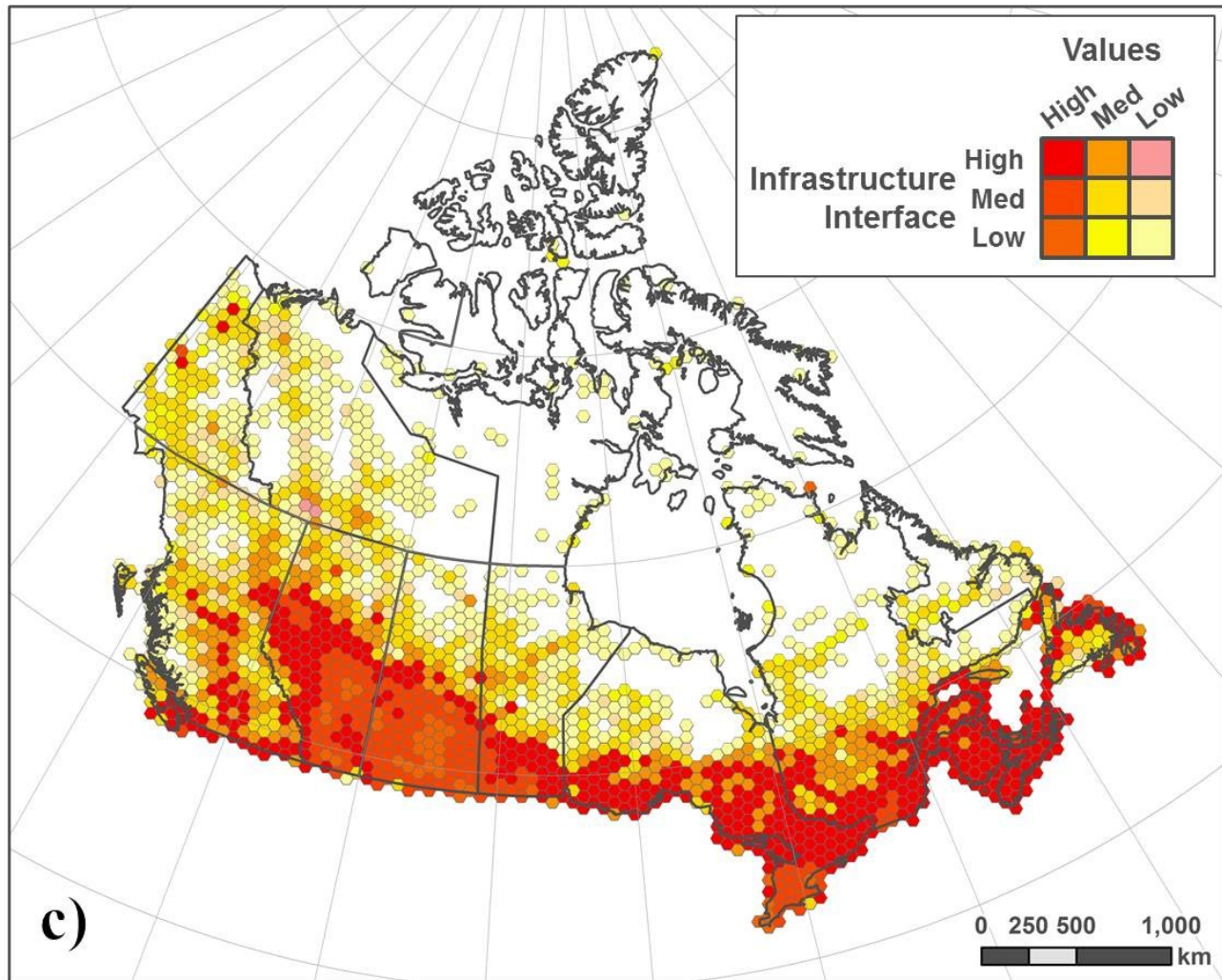
Figure 3-14. Categorical national map of interface areas by human-built structures or values.
Categories of structure or value density (structure or value area as a percent of land area in each hexagonal cell) crossed with categories of interface density (interface area as a percent of land area in each hexagonal cell) within hexagonal ~1 degree cells (exact cell area is 3400 km^2, which is ~1 degree by 1 degree at mid-latitudes of Canada) for **a)** wildland-urban interface (categories: high > 6%, medium > 1 – 6%, low ≤ 1%) with urban structures (categories: high > 0.06%, medium > 0.005 – 0.06%, low ≤ 0.005%), **b)** wildland-industrial interface (categories: high > 3%, medium > 0.5 – 3%, low ≤ 0.5%) with industrial structures (categories: high > 0.05%, medium > 0.009 – 3%, low ≤ 0.009%)), and **c)** infrastructure interface (categories: high > 25%, medium > 7 – 25%, low ≤ 7%) with infrastructure values (categories: high > 0.6%, medium > 0.09 – 0.6%, low ≤ 0.9%.

Despite having high-resolution structure or value locations from the CanVec+ dataset, the dataset does not necessarily define single structures or homes. For example, a structure point or polygon could potentially represent a single-family dwelling, or a multi-story apartment complex. Therefore, in this study, no estimate of the number of homes or how much of the human population is living or working within interface areas can be produced. To address this limitation to some degree, the WUI map was overlaid with a layer of "Populated Places" from the North American Atlas dataset (Natural Resources Canada 2010). This dataset provides point locations for cities, towns, settlements, and reservations across Canada (and the rest of North America). Of all the Canadian Populated Places, 521 of 544 locations (96%) had at least some WUI within a 5 km buffer. The majority (60%) of Populated Places also had more than 500 ha[9] of WUI within a 5 km buffer (327 of the total 544). WII and infrastructure interface were not considered here since the Populated Places dataset reflects human populations in settlements, not the industrial structural locations or infrastructure with no population associated with it.

The Populated Places dataset also classifies each point into four categories of population; Figure 3-15 shows each "Populated Place" with point sizes reflecting relative population, and each point is colour coded as to whether it has more than 500 ha of WUI within a 5 km buffer from the point centroid. For Populated Places such as small villages, towns, and Aboriginal reserves (population 1 – 9 999), 65% of settlements have more than the 500 ha of WUI (267 of 412). For cities (population 10 000 – 99 999), 87% (89 of 102) meet this criteria. Large cities (population 100 000 – 999 999) have 54% (15 of 28), and metropolis areas (population > 1 million) have no places meeting this criteria (0 of 2). Note that the "Populated Places" are considered a point with a 5 km buffer to determine if it contains WUI; the entire population within the "Populated Place" is (in most cases) not directly surrounded by WUI. This analysis just provides an overview of how many "Populated Places" in Canada may have substantial WUI area near them.

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[9] *The value of 500 hectares is considered since it represents a sizeable area of interface land which could potentially impose a risk to a community, and also this 500 hectare value was used in several WUI mapping studies (starting with Radeloff et al. 2005) as part of the fuels definition.*
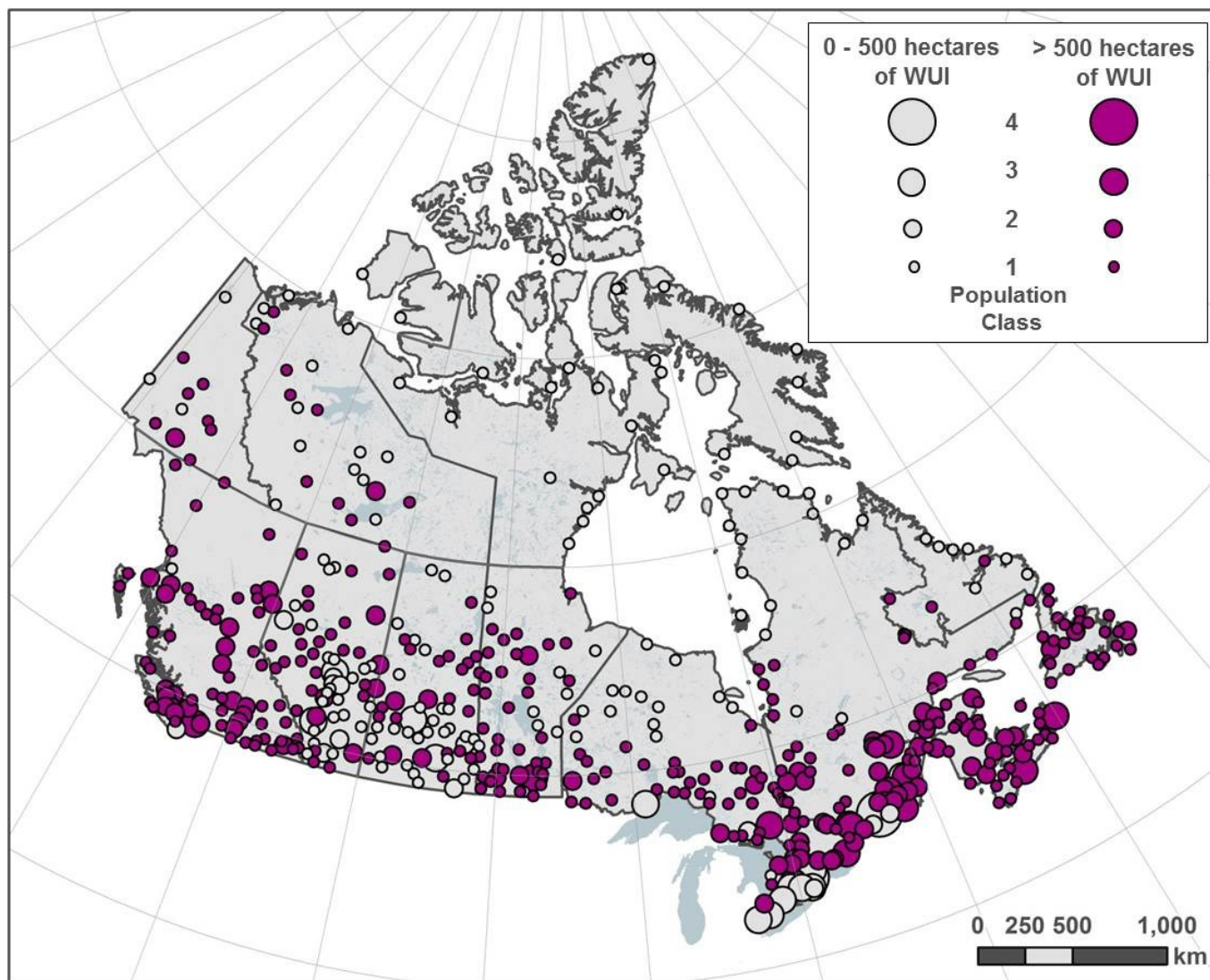
Figure 3-15. "Populated Places" in Canada with substantial wildland-urban interface areas.
Map of "Populated Places" by relative population size ("Population Class" 4 = population of over 1 000 000, 3 = 100 000 – 999 999, 2 = 10 000 – 99 999, 1 = 1 – 9 999) in Canada; points shown in purple indicate a substantial amount of wildland-urban interface (WUI; > 500 hectares) and points in grey indicate very little (possibly zero) WUI (0 – 500 hectares).

3.4   Fires and Interface

The relationship between past fire area burned and interface areas are investigated in this section. Data on past fire locations, area burned, and causes were obtained from the Canadian Forest Service Canadian National Fire Database (NFDB) (Canadian Forest Service 2014). Figure 3-16 displays all fire area burned polygons that are recorded in the NFDB from 1980-2014, and displays each fire as an "interface fire" or "not interface fire" for the WUI (Figure 3-16a), WII (Figure 3-16b), and infrastructure interface (Figure 3-16c). To be counted as an interface fire, any part of the fire polygon must intersect with an interface area (even a small part). It should be noted that the interface areas are mapped using more current data than much of the NFDB, so it is possible that fires deemed "interface fires" may not have actually been interface fires if the area of interface did not exist at the time of the fire. This analysis could be thought of an indication of if those fires happened at the present time, would they be "interface" fires or not. For the WUI, 17% of all NFDB fire polygons are considered to be an interface fire. For WII, 6% of fire polygons are interface fires, and for infrastructure interface 38% of fire polygons are interface fires. The same classification was performed, but with the fire polygons grouped into lightning-caused or human-caused fires (leaving out other causes: unknown, restarts, prescribed burns). Lightning-caused fires saw much lower percentages of "interface fires", with 6%, 3%, and 25% being classified as interface fires for WUI, WII, and infrastructure interface, respectively. Human-caused fires had higher percentages, with 39%, 12%, and 65% for WUI, WII, and infrastructure interface, respectively. Note that the overall number of fires is underestimated here; the NFDB polygons do not include all fires (especially underrepresenting smaller fires), and only provincial/territorial data and data from Parks Canada are reported (leaving out municipal and undetected fires).

Legend:
- Not Wildland-Urban Interface Fire
- Wildland-Urban Interface Fire

a)
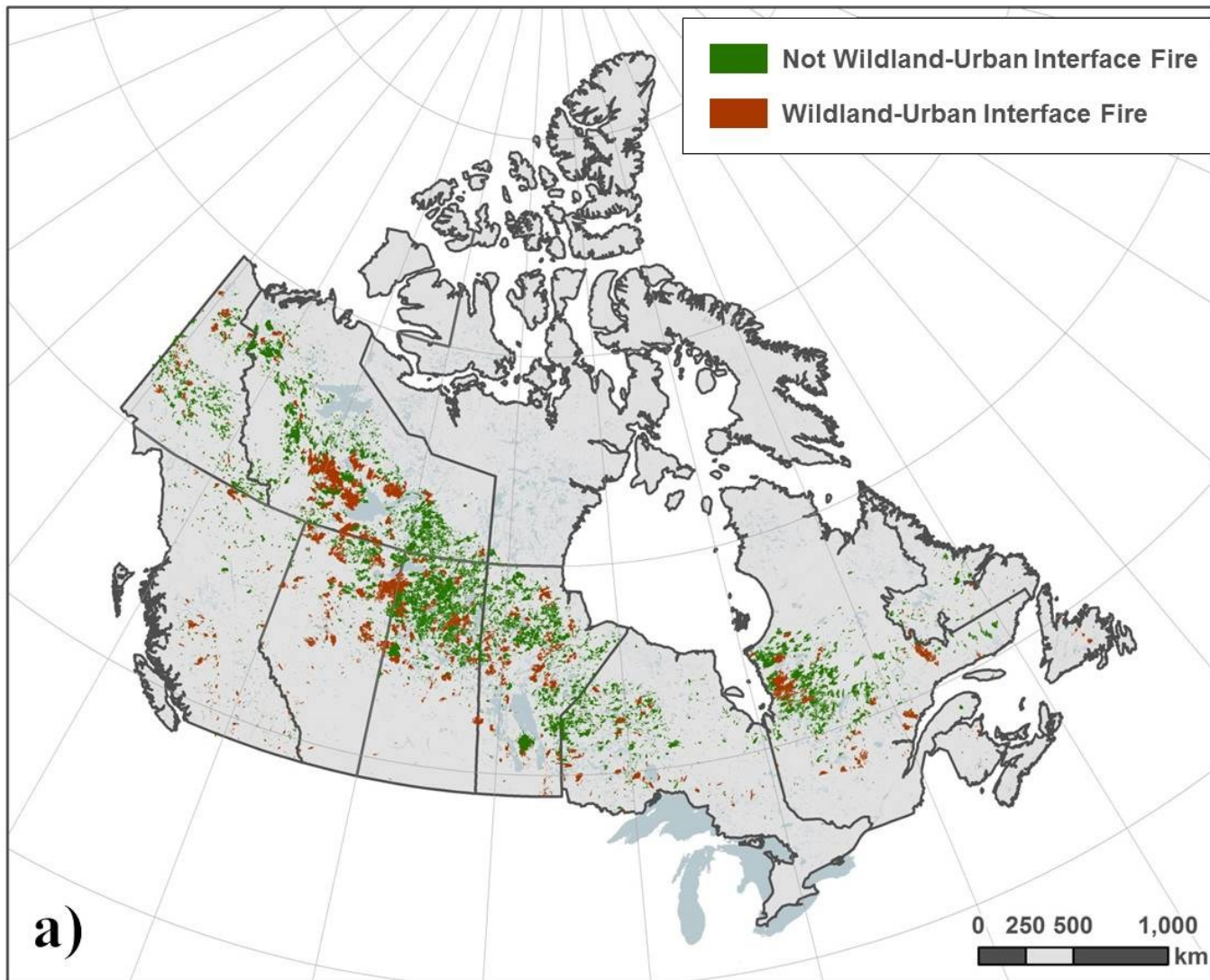
(Figure 3-16 continues on next page)
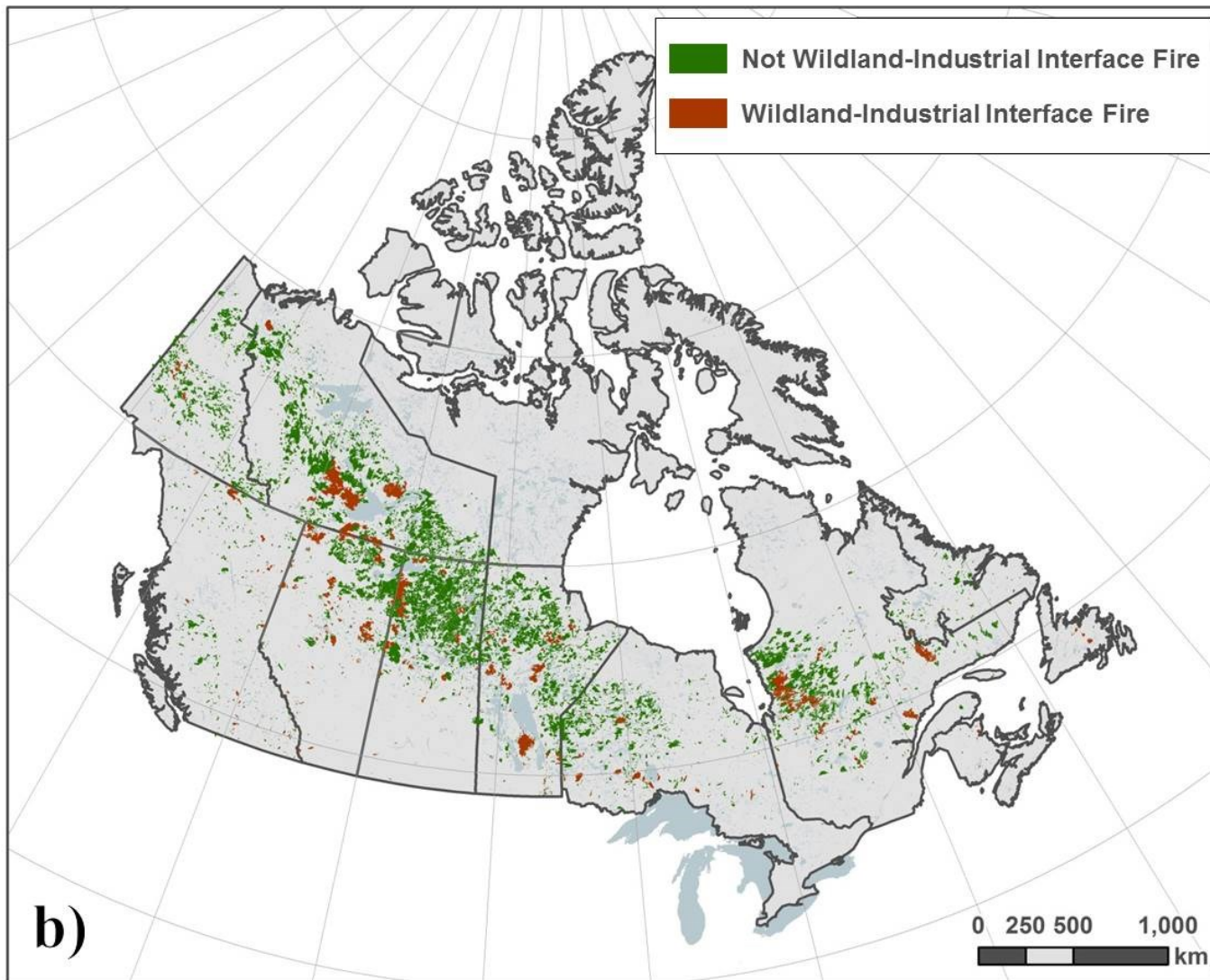
(Figure 3-16 continues on next page)
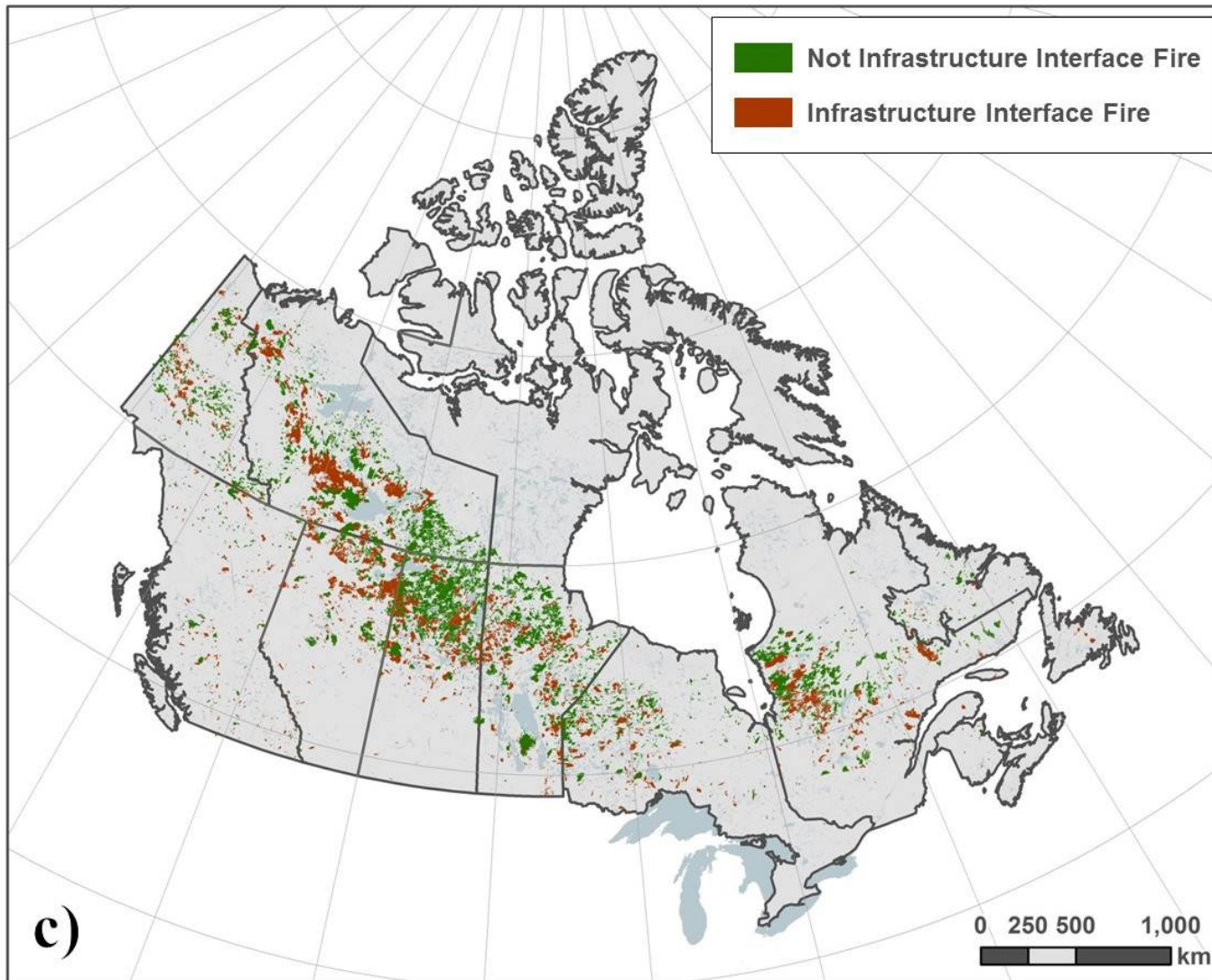
Figure 3-16. Past fires, classified as "interface fire" or "not interface fire".
Fire polygons from the Canadian National Fire Database (NFDB) (Canadian Forest Service 2014) from 1980-2014, classified as "not interface fire" (green) and "interface fire" (red) based intersection of past fire polygons with current interface area for **a)** wildland-urban interface, **b)** wildland-industrial interface, and **c)** infrastructure interface.

To look at the relationship between fires and interface areas, data on fire area burned, number of fires, and interface area were aggregated into hexagonal cells (as was done with fuels and structures in sections 3.3.1 and 3.3.2, respectively). The same categories of interface area were used (high/medium/low, with the same category values). Area burned for each hexagonal cell was determined by individually adding the area burned for each fire polygon (or partial polygon) within the hexagon. Overlapping fire polygons were permitted; therefore it is possible for much more than 100% of a hexagon cell to have burned over the 1980-2014 time period. Numbers of fires per hexagonal cells were determined by using the NFDB points dataset, which shows the location of recorded fires in Canada as a point feature. Within each cell, the number of fire points were counted to produce the number of fires per cell. The three categories of interface were crossed with three categories of fire area burned (high/medium/low; Figure 3-17a for WUI, Figure 3-17c for WII, and Figure 3-17e for infrastructure interface) or number of fires (high/medium/low; Figure 3-17b for WUI, Figure 3-17d for WII, and Figure 3-17f for infrastructure interface) in each hexagonal cell. With the fuel categorical maps, it is not possible that there is an interface area without fuel (since the interface definition requires the presence of wildland fuels). However, with these fire categorical maps, it is possible to have interface areas existing with areas of no historical area burned or number of fires; in Figure 3-17 this case of zero fire is displayed as an additional category (grey cells).

For all three interface types, when crossed with area burned the distribution of the higher categories (e.g. high/high, high/medium, medium/medium) are generally distributed to a more northern extent when compared to the same maps using number of fires. For the maps using area burned (Figure 3-17a, c, e), the majority of the boreal forest contains hexagons with higher categories. The prairies, southern Ontario and Quebec, the east coast provinces, and the far north have very low or no area burned, resulting in a zero or low category for area burned by interface. A difference between northwest and northeast Ontario can also be seen, with higher categories for the majority of cells in northwestern Ontario. For the maps using number of fires (Figure 3-17b, d, f), in addition to a more southern distribution of the higher categories than is seen for the area burned maps, there are also areas of higher categories in southern Ontario and Quebec and the east coast provinces (except for Newfoundland). The prairies have slightly higher values than were found for the area burned maps, but still mostly one of the lower categories or no fire. As with the area burned maps, the number of fire maps all show the far north with the no fire category.
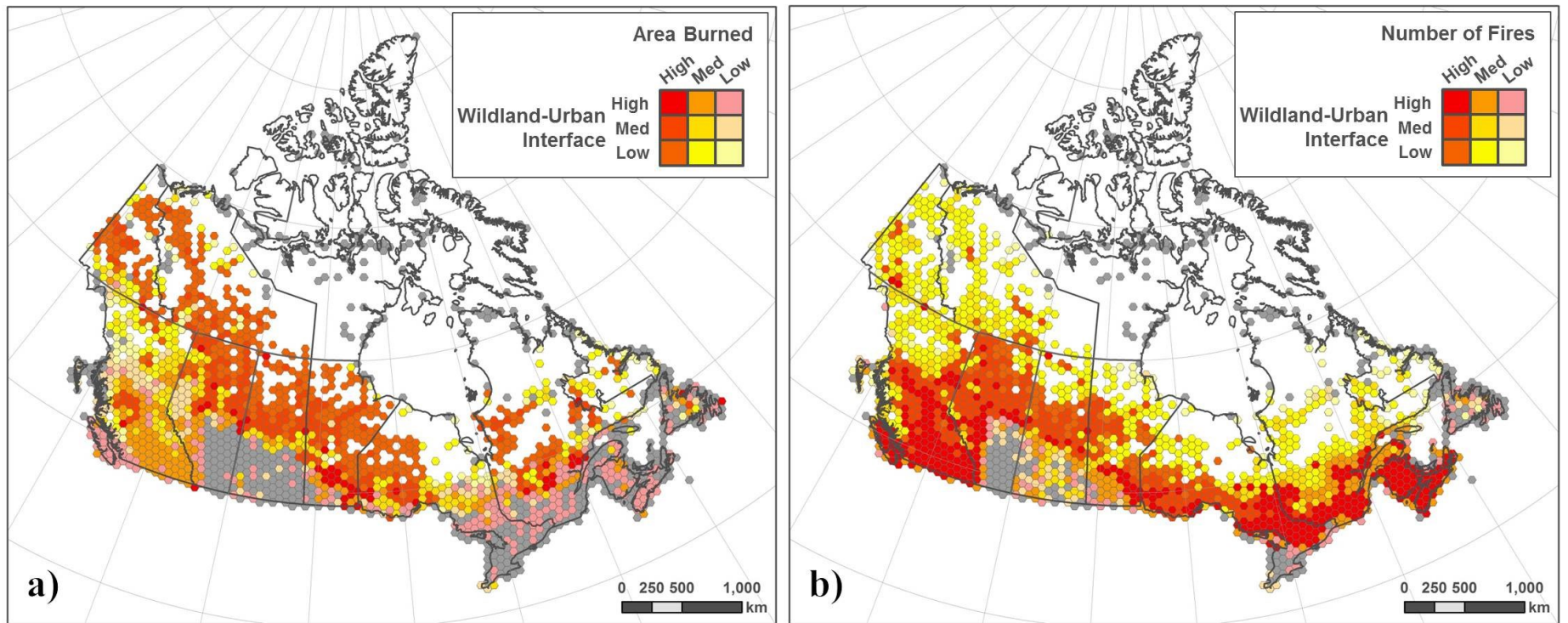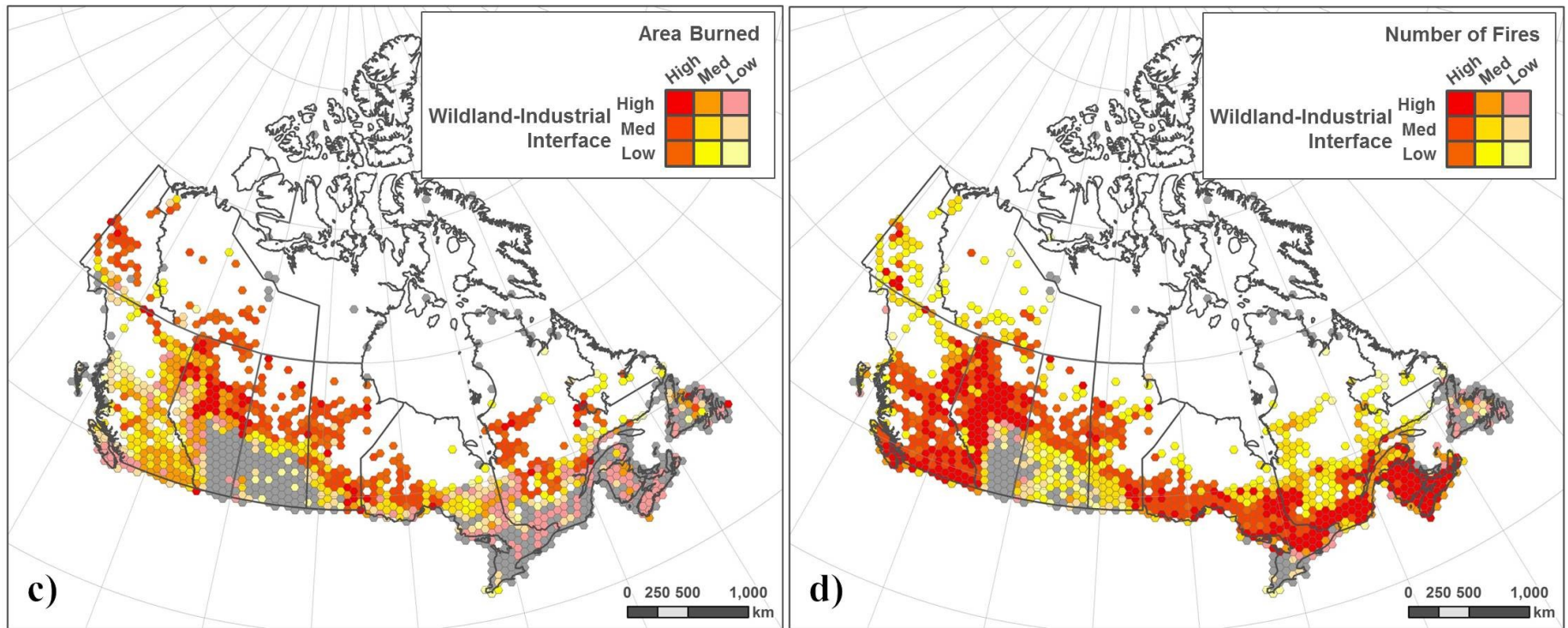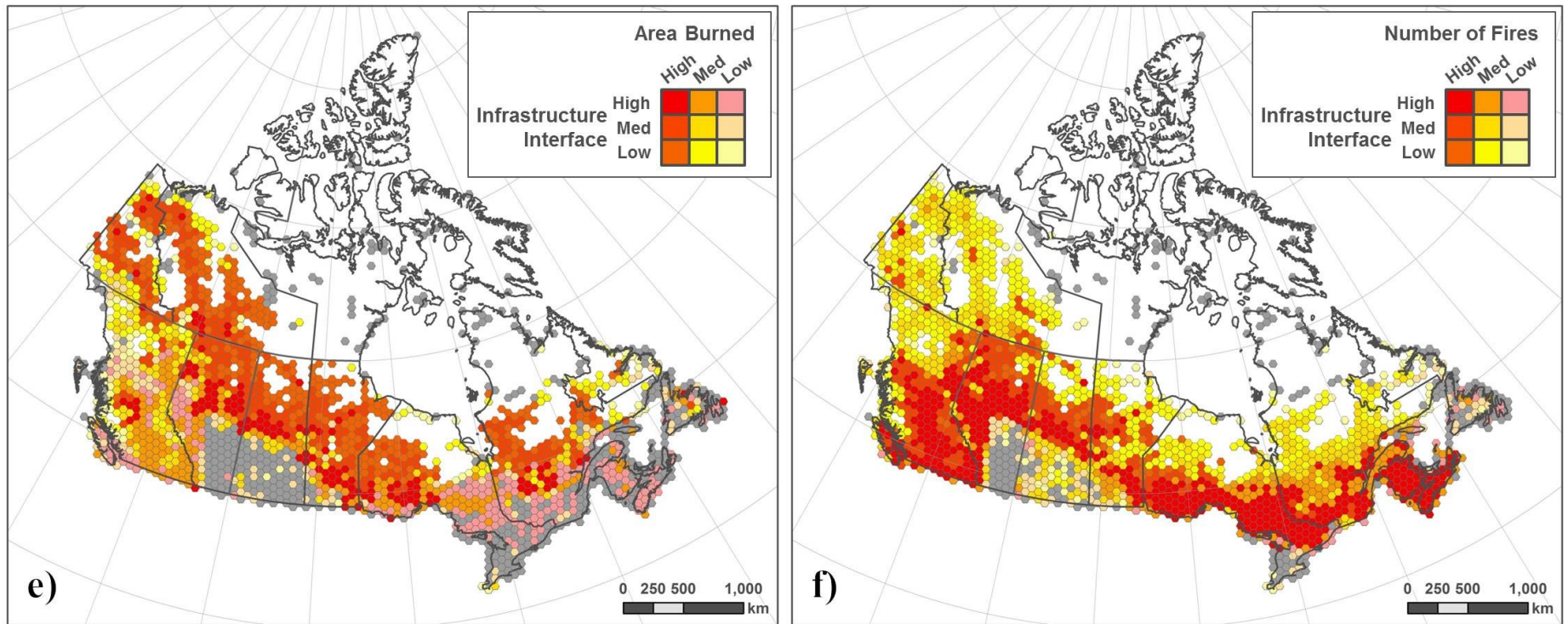
(Figure 3-17 continues on next page)

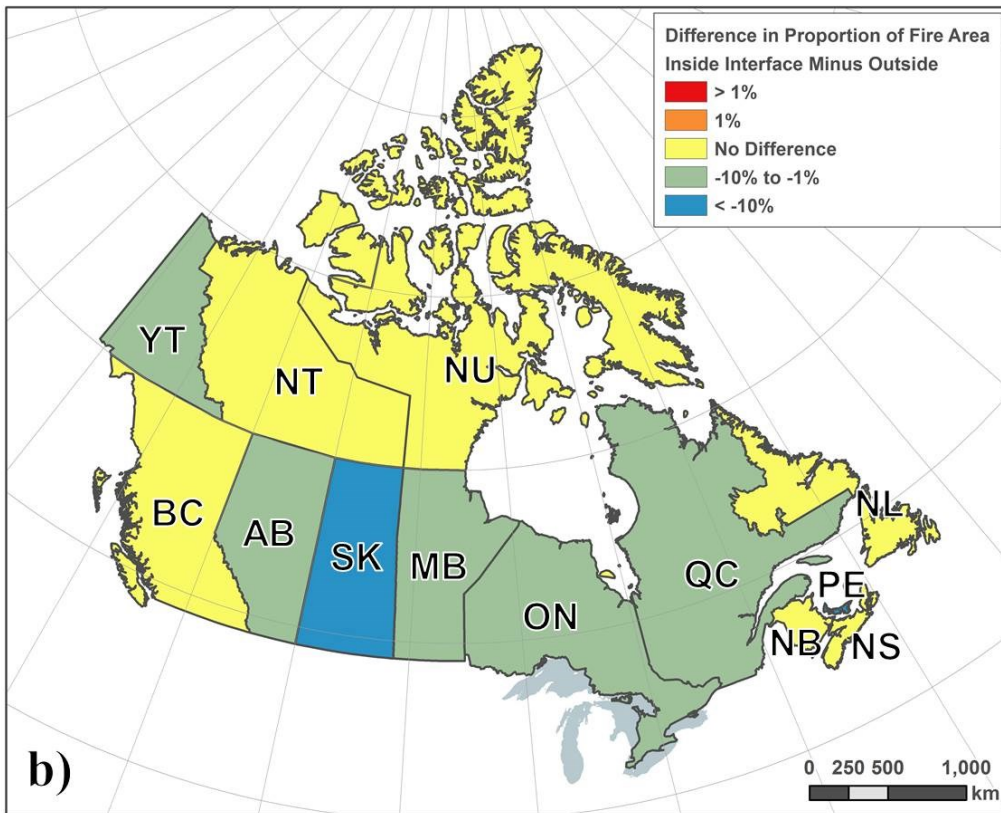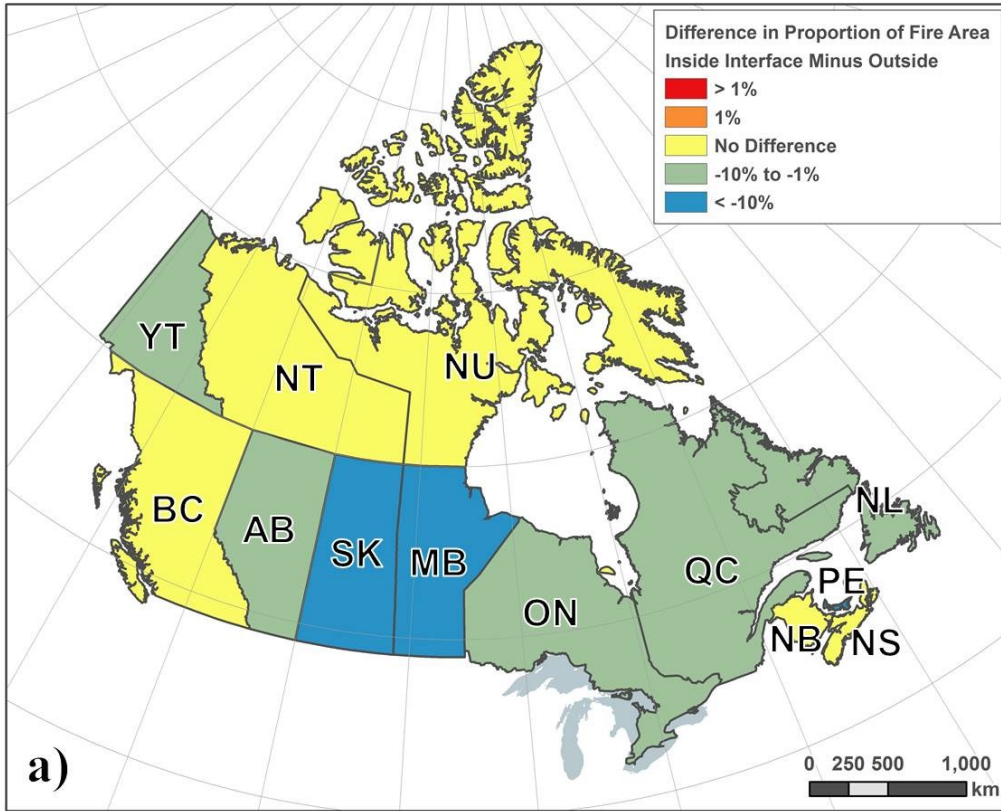*(Figure 3-17 continues on next page)*

Figure 3-17. Categorical national maps of interface areas by fire area burned or numbers.

Categories of area burned density (area burned as a percent of land area in each hexagonal cell; a, c, e) or number of fires (total number of fires in each hexagonal cell; b, d, f) crossed with categories of interface density (interface area as a percent of land area in each hexagonal cell) within hexagonal ~1 degree cells (exact cell area is 3400 km2, which is ~1 degree by 1 degree at mid-latitudes of Canada) for a, b) wildland-urban interface (WUI), c, d) wildland-industrial interface (WII), and e, f) infrastructure interface. Categories (as % of cell land area) of fire area burned density are high (> 30%), medium (> 2 – 30%), low (≤ 2%); categories (as number per hexagonal cell) of number of fires are high (> 100), medium (6 – 100), low (≤ 5). Additionally, for area burned density and for number of fires, an additional category is added (grey cells) to indicate cells with zero area burned or zero number of fires. Categories for WUI are high (> 6%), medium (< 1 – 6%), low (≤ 1%); categories for WII are high (> 3%), medium (> 0.5 – 3%), low(≤ 0.5%); categories for infrastructure interface are high (> 25%), medium (> 7 – 25%), low (≤ 7%).

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To determine if there has been less fire burned inside current interface areas compared to outside interface areas, a similar analysis was performed as in section 3.3.1 for "high hazard" fuels. Randomly sampled points were selected across the entire land area of each province, with the number of random samples proportional to 0.01% of provincial/territorial land area. Using the randomly sampled points, χ^2-tests for equality of proportions were performed for each province and territory (with $\alpha = 0.05$ and $n = 1500$). Fire polygons used in this analysis are the same 1980-2014 NFDB polygons which were mentioned previously. A sample point was considered to be a "fire" sample point if one or more fire polygons intersect it. As with the analysis of the number of NFDB polygons classified as "interface fires" (beginning of section 3.4), this analysis uses past fires but current interface areas and thus some areas of interface may not have been interface when the fire burned.

Nationally, it was found that there is a lower proportion of area burned within interface areas compared to outside interface areas. For WUI, the proportion of points sampled inside WUI areas that had been burned by fire is 2%, compared to 8% outside (difference of 6%, $\chi^2 = 65$, p-value < 0.0001). For WII, the proportion of fire samples inside WII areas is 4%, and 8% outside (difference of 4%, $\chi^2 = 28$, p-value < 0.0001). Infrastructure interface has a proportion of 6% inside and 9% outside (difference of 3%, $\chi^2 = 10$, p-value = 0.001). Figure 3-18 shows the results for WUI (Figure 3-18a), WII (Figure 3-18b), and infrastructure interface (Figure 3-18c) by province and territory. The majority of provinces and territories follow the national findings, with less fire area inside interface areas than outside (ranging from 2% to 83% less; p-value <0.005). However, some provinces/territories show no significant difference in the amount of fire inside vs. outside interface areas (p-value > 0.05; shown in yellow as "No Difference" in Figure 3-18).

(Figure 3-18 continues on next page)

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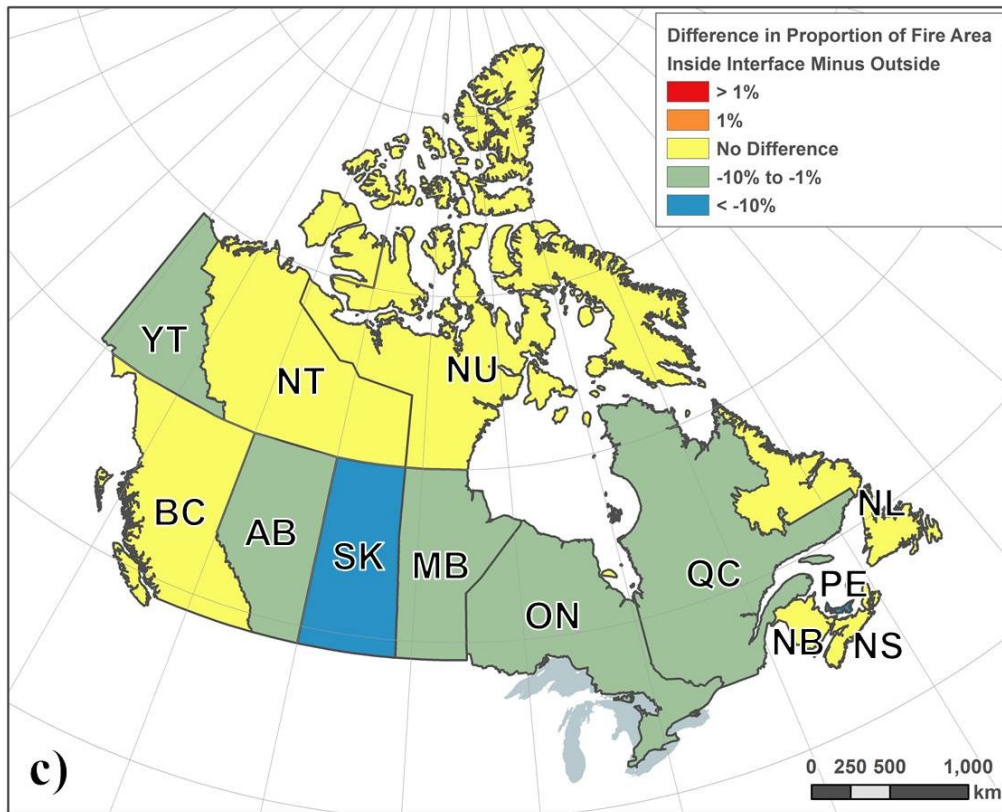
Figure 3-18. Provincial/territorial choropleth maps of difference in proportion of fire area.
Choropleth maps of difference in proportion of fire area burned inside interface areas compared to outside interface areas by province or territory for **a)** wildland-urban interface, **b)** wildland-industrial interface, and **c)** infrastructure interface. Red and orange colours indicate a statistically significant higher proportion of land that has seen fire inside interface areas within a province/territory; green and blue colours indicate a statistically significant lower proportion; yellow indicates no statistical difference ($\alpha = 0.05$) in proportion of area that has seen fire inside vs. outside interface areas.

4   DISCUSSION

In this chapter, a discussion of the results of this study will be presented. Possible explanations for the patterns observed will be discussed, along with the implications of the results. Applications of the results will be mentioned, but will be discussed in detail in section 4.2. A discussion of fire risk in the interface will also be presented, as will a comparison of the results from this study to other studies.

4.1.1   *Interface Discussion*

With a total of 116.5 million ha of interface (32.3 million ha of WUI, 10.5 million ha of WII, and 109.8 million ha of infrastructure interface), Canada has an extremely large land base with the potential for interface fire risk (13.8% of its land area overall). Though these areas may not actually be at risk of wildfire (see section 4.1.5 for discussion of interface and risk), classifying these areas as "interface" indicates the potential for risk in the case of a wildfire under appropriate conditions. Interface areas delineated here are areas where intensive fire suppression and values protection activities would likely be required, and should be considered priority areas for fire mitigation activities (e.g. FireSmart, community preparedness plans, and fuel treatments).

Unfortunately, due to limitations of the input data, no estimate of the number of people or the number of structures in the interface could be made in this study. However, it was found that the majority of named cities, towns, villages, reserves (60%) do have a substantial amount of WUI surrounding them (i.e. at least 500 ha within a 5 km buffer), and almost all places (96%) have at least some amount of WUI (i.e. > 0 ha within a 5 km buffer). Cities and smaller villages, towns, and aboriginal reserves are more often surrounded by significant WUI areas, as compared to large cities and metropolis areas. Compared to the rest of Canada, more locations in the far north, the prairies, and southern Ontario have only small amounts or no WUI area surrounding them. Overall, the large area covered by interface, and the fact that the majority of populated places have interface surrounding them indicates that Canada certainly has a potential interface problem.

The main products of this study are the three maps of interface (WUI, WII, and infrastructure interface). Images of the national maps are provided (Figure 3-1, Figure 3-3, Figure 3-4, Figure 3-5) along with the provincial maps in Appendix 2. Full-resolution maps are

available by request, on scales from case study areas to national. These maps may be used for further research, or for practical applications (discussed in section 4.2), keeping in mind the limitations and appropriate usage outlined in sections 2.4 and 4.2.

The three different interface types may require varying priorities and approaches to fire protection or mitigation. All structures included as input into calculating interface areas potentially require fire suppression and/or values protection to defend them from wildfire. The 32.3 million ha of WUI is the highest priority interface type, since it represents communities and homes. These structures also typically ignite easily, compared to many large industrial structures mapped as WII (10.5 million ha); in most cases, the WUI would require a greater fire suppression and values protection effort. Conversely, in many cases for large industrial structures, fire breaks and values protection in the form of sprinklers may be sufficient for protection. Infrastructure interface logically receives the lowest priority since homes, businesses, and expensive industrial structures are not involved. However, the infrastructure interface can be subject to expensive damages, may be important to protect for indirect reasons (e.g. roads as escape routes), and additionally, critical infrastructure disruptions to communities and industry can have negative impacts. For example, power outages due to wildfire can force communities to have extended evacuation times, disrupt daily life for residents, and result in losses for businesses and industry. Another example of the importance of the infrastructure interface is protection of infrastructure critical for community protection. In the 2016 Fort McMurray wildfires, public water utilities personnel worked overtime to ensure the water supply infrastructure was running and protected from direct fire threat (Stewart and Reith 2016); without access to water, values protection for the area would have been much more challenging. The infrastructure values included in the infrastructure interface map here may potentially require fire suppression to prevent these negative impacts, which provides a challenge due to the large area the infrastructure interface covers (109.8 million ha). However, infrastructure values may also offer opportunities for fire suppression activities, such as fire breaks or boundaries for burn out operations in the form of roads or powerline right of ways (once greened up).

The interface presents a complex problem across Canada, but some areas are of particular concern. Quebec has the largest area of WUI, the third largest area of WII, and the second largest area of infrastructure interface. There is also a high density (i.e. area of interface as a percentage of land area) of interface in the southern portion of the province. Quebec can have very active

fire seasons, and sees an annual average area burned of over 350 000 ha (Canadian Forest Service 2014); combined with the large amounts of interface, it means that interface fire is an important issue in Quebec. Alberta has the fourth largest area of WUI, and the third largest area for infrastructure interface, but is by far the dominant province for amount of WII area. Alberta has almost double the WII area as the next highest province, which can be mostly explained by the large oil and gas industrial operations in the province, which are rapidly expanding (McGee *et al.* 2014; Canadian Council of Forest Ministers 2016). Many of these oil and gas operation locations are located in the highly vegetated boreal forest, resulting in large WII areas in the province. Ontario comes in second for the amount of WUI, third for WII, and also has the largest infrastructure interface area. Ontario has a large population which (other than southern Ontario and some larger cities) is rural and dispersed (Bollman and Clemenson 2006), requiring a large road network and many power and transmission lines. Ontario also shows high interface densities (interface area as a percentage of land area) for much of central Ontario (including the Muskoka region). British Columbia has the third largest WUI area, second largest WII area, and fourth largest infrastructure interface area; all primarily concentrated in the interior of the province where fire activity is highest (Stocks *et al.* 2002). The four provinces mentioned here with the largest interface areas (Quebec, Alberta, Ontario, and British Columbia) incidentally are the four main players in fire management; these four provinces are responsible for spending around 80% of the money spent on fire management across the country (Stocks and Flannigan 2013).

Most of eastern Canada, specifically the provinces of Nova Scotia, Prince Edward Island, and New Brunswick have particularly high densities of interface (but not high total areas), especially for WUI and infrastructure interface. A drastically higher percentage of land classified as interface in these three provinces is found, compared to percentages outside these three provinces. Wildfire in these provinces is less frequent and lower probability than in other provinces (Stocks *et al.* 2002), so the high density of interface area is not as big of an issue as it could be. However, if a wildfire occurs in these three provinces, it is very likely to be an interface fire. Over 30 evacuations due to wildfire have occurred from 1980-2007 in these three provinces (Figure 1-2); more recently, a notable interface fire occurred in Nova Scotia in 2009 when 1200 people from Halifax were evacuated and ten homes were destroyed (CBC News 2009; Whitman *et al.* 2013).

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The far north of Canada has much less potential for interface fire problems. Though the north does have some limited areas of interface, the low fire occurrence, low fuel hazard, and low potential fire risk (Stocks *et al.* 2002) mean that these areas would not be considered to have an interface fire issue. In fact, suppression capacity is much lower in most of the north; in particular in Nunavut there is no wildfire firefighting service. Additionally, southern Ontario and the prairies would be considered to have a much lesser interface fire problem than compared to other areas (e.g. boreal forest). Most of southern Ontario and the prairies have low densities of interface areas due to limited fuels, but these areas do have high structure density. However, that is not to say that some northern communities or areas with low fuel density and high structure density could not be challenged by fire under the right conditions. For example, many Aboriginal and northern communities are particularly vulnerable to the negative impacts (including social impacts) of fire due to their remote locations and their limited suppression infrastructure and capacity (Christianson 2015).

4.1.2 Fuels and Interface Discussion

Canada has a large amount of wildland fuels (covering 67% of the total land area). Much of this fuel area is not classified as interface (with 5.8% of fuel area classified as WUI, 1.9% as WII, and 19.5% as infrastructure interface). However, a much larger area than just the interface in Canada may require fire suppression in order to mitigate direct threats to communities. For example, fire suppression on an actively burning wildfire should begin long before it reaches 2.4 km from a community. The fuel areas deemed to be interface areas here would require direct fire suppression and fire mitigation, but the fire suppression activities would ideally have begun far outside the interface.

Areas of Canada where fuels are limited are areas of less concern to wildland firefighters. Fuels may be limited due to environmental restrictions on vegetation growth (e.g. the northern parts of the country near the treeline) or human-induced influences on fuels (e.g. irrigated agricultural areas and densely developed urban or suburban areas). If areas with high fuel density coincide with significant densities of interface areas they become the areas of most concern for wildland firefighters due to the high potential for destruction. Specifically, grid cells shown in the higher categories of fuel density crossed with interface density (i.e. the red and orange cells in Figure 3-12) indicate the areas that may be of most concern. Broad areas of most concern

include populated areas within the boreal forest across the country (particularly in the southerly parts of the boreal), the east coast, and interior British Columbia.

Results from this study provide information on fuel characteristics inside interface areas as compared to outside interface areas. Fuels categorized as "high hazard" (see section 3.3.1) were found to be much more common within interface areas (with 90-93% of fuel area being high risk inside interface areas but 74-76% outside interface areas). This result means that fighting a fire within interface areas will generally be more challenging due to a higher fuel hazard and potentially more extreme fire behaviour. This result could be explained by a variety of factors, including: communities are more often built near or in areas with more higher hazard fuel for the natural amenity benefits, development may also occur less frequently in sparsely vegetated or barren areas, and also in general there is much less population, industry, and infrastructure in northern sparsely vegetated areas. Additionally, this result is partly an artifact of the method of interface calculation. The interface calculation requires the fuels as input, and the variable-width buffer weights the higher hazard fuels as a larger buffer. Therefore, structures with larger areas of high hazard fuels surrounding them will intrinsically have larger interface areas.

4.1.3 Structures and Interface Discussion

Across Canada, there are large areas with higher densities of structures (or values) found with higher densities of interface areas (i.e. the red and/or orange cells in Figure 3-14). Though these areas do indicate an increased density of structures or values within the cell, many of the structures or values may not have high fire risk (discussed in section 4.1.5). Higher structure density (unlike higher fuel density discussed in section 4.1.2) does not necessarily indicate a more challenging fire situation; the effects of more structures on the landscape are complex. For example, building a structure may increase the area of interface if built next to or amongst wildland fuels, or building a structure may decrease interface area if built within an existing interface community. Furthermore, the direct and indirect impacts of development can mean that forests become more susceptible to pests and disease and the probability of ignition increases due to human-caused ignitions, resulting in an increased fire hazard in the interface areas (Davis 1990; Syphard *et al.* 2012; Bar-Massada *et al.* 2014; Parisien *et al.* 2016). Conversely, fire probability and fire spread has been observed to decrease across North America with increased

human development, which is likely due to multiple factors, including: more fire suppression resources, better access for suppression, easier fire suppression for dense urban areas compared to more isolated structures surrounded by fuels, and increased landscape fragmentation preventing fire spread (Syphard *et al.* 2012; Wang *et al.* 2014b; Parisien *et al.* 2016). Dense development of structures can also directly cause a decrease in wildland fuels (Liu *et al.* 2007), thus reducing the interface area due to fuel limitation. An example of how dense structure development can limit the interface area can be seen in southern Ontario and Quebec, with limited density of interface and fewer "Populated Places" deemed to have significant amounts of WUI surrounding them. Furthermore, of all "Populated Places" across the country, a much lower percentage of the larger places (large cities, metropolis areas) are considered to have significant amounts of WUI as compared to smaller places (e.g. cities, towns). This is likely due to the extreme amounts of development and removal of natural fuel areas.

In this study, the assumption was made that all structures included in the interface calculation are equally and easily ignitable in order to simplify data requirements at a national scale (as discussed in section 2.4). However, specific structure characteristics create large variation in structure ignition (Cohen 2000; Caballero *et al.* 2007; Mell *et al.* 2010; Calkin *et al.* 2014). It has been pointed out that if structures were less flammable and built to resist wildland fires (e.g. adhering to FireSmart guidelines by using fire-resistant building materials and clearing the land surrounding structures) then the interface fire problem becomes much less of an issue (Cohen 2000).

A second assumption in this study concerning the structures or values was made when producing the area estimates for the hexagonal cells. A structure or value can be represented in the input data as simply a point or thin line, but to produce the structure or value raster it was assumed that the area of these point or line features was one raster cell in size (~30 m x 30 m). For point features, the raster cell which the point's centroid falls within was classified as a "structure" cell, and for linear features any cell it intersects is classified as a "value" cell. This assumption will overestimate structure or value density for small structures, and underestimate for larger structures (though larger structures are generally included in the original dataset as polygons). This assumption affects the results for Figure 3-14, but does not affect the interface calculations or maps.

4.1.4   Fires and Interface Discussion

Wildfires within areas defined as interface areas in this study were shown to be fairly common; of all mapped fire polygons across the country from 1980-2014, 17% were found to overlap with current WUI areas (i.e. "WUI fires"), 6% overlapped with WII areas (i.e. "WII fires"), and 38% overlapped with infrastructure interface (i.e. "infrastructure interface fires"). These numbers do not reflect the true fire activity, since fires (especially those near interface areas) are actively suppressed. In fact, in this study it was found that there is generally less past fire area burned within current interface areas compared to outside interface areas. It is very likely that early detection and fire suppression (in particular initial attack) are the main factors in this reduction of fire area within interface areas. It should be noted that some fires deemed "interface fires" or the larger area burned outside interface areas may be overestimated, since past fire activity (1980-2014) was used alongside current interface areas. This could result in fires in the past being deemed to be interface fires when really there was no interface at the time of the fire.

The finding in this study that lightning-caused fires have much lower percentages of fires within interface areas (6%, 3%, and 25% for the WUI, WII, and infrastructure interface, respectively) as compared to human-caused fires (39%, 12%, and 65% for the WUI, WII, and infrastructure interface, respectively) is a logical result when considering human-caused ignitions are more frequent near interface areas where humans are more likely to be. Lightning-caused fires, however, are not clustered around populated areas and can be difficult to access and suppress (Stocks *et al.* 2002; Podur *et al.* 2003; Stocks and Flannigan 2013), resulting in low suppression effectiveness (Arienti *et al.* 2006; Robinne *et al.* 2016). Lightning fires can grow to a greater extent in the less populated boreal forest where, in some cases, they may be permitted to burn freely if not threatening values (Stocks and Simard 1993; Stocks *et al.* 2002; Podur *et al.* 2003; Canadian Forest Service 2014).

Patterns in the distribution of areas with high amounts of fire and high amounts of interface vary depending on whether the fire component is considered as area burned or as the number of fires. With area burned, there is much more area burned in more northern areas (e.g. boreal forest; see Figure 1-1). When combined with categories of interface, the categories of most concern (i.e. areas with both high interface and high fire) shift noticeably northward to where the majority of area burned resides. With number of fires, the categories of most concern

are present in the southern boreal and even farther south, following the distribution of the number of fires in Canada (Stocks *et al.* 2002; Canadian Forest Service 2014). Areas with historically low area burned or number of fires (e.g. east coast, prairies, southern Ontario and Quebec), despite having substantial interface areas, may receive a low value in the category of fire and interface (see grey, yellow, or pink cells in Figure 3-17). This classification hints at the element of fire risk; just because an area is classified as interface in this study does not necessarily mean it is at risk from wildland fire.

4.1.5   *Interface and Risk*

In general terms, "risk" is the product of the chance of exposure to a disaster and the impacts of that disaster. In the case of wildland fire, risk is typically defined as the burn probability (i.e. the chance a given location will have a fire in a given period of time), fire hazard, or fire danger multiplied by various metrics for potential impacts or vulnerability (e.g. population affected, housing density, monetary costs of structures) (Fried *et al.* 1999; Lein and Stump 2009; Haas *et al.* 2013; Chuvieco *et al.* 2014). Interface areas defined in this and other studies are not necessarily at risk to wildland fire, and conversely, areas not mapped as interface may still be at risk to wildland fire (as mentioned previously in section 2.4). Differing fire risks can be produced from a wide variety of factors, including: fire regimes, fire behaviour, weather, climate, fuel structure, fuel load, fuel type, topography, ecological values, socioeconomic values, structure building materials, landscaping around structures, accessibility of fire suppression equipment, and effectiveness of suppression activities (Radeloff *et al.* 2005; Haas *et al.* 2013; Chuvieco *et al.* 2014).

This study did not map fire risk across Canada, only the interface areas across Canada that may potentially be at risk of damage from wildland fire. A full risk assessment within interface areas is planned for future research activities (see section 5.1). However, some of the analysis of the interface maps does incorporate some elements of fire risk for the mapped interface areas. For example, Figure 3-17 shows interface areas and fire activity (area burned or number of fires) aggregated over ~1 degree cells. Cells shown in grey indicate areas of these maps that were found to have some interface area, but then had either no area burned or zero fires. According to the risk definition, these areas would be considered not at risk (or at least

very low risk) since there is historically no exposure to fire[10]. Some areas of Canada found to have particularly high percentages of interface (e.g. Nova Scotia, New Brunswick, and Prince Edward Island) are likely at much lower risk because of the lower fire activity in these areas (Stocks *et al.* 2002). However, in the case of a wildland fire in these provinces, it is more likely to be an interface fire than in other provinces due to the higher density of interface. It should be mentioned that climate change effects on vegetation and fire activity may mean that the historical patterns of fire are no longer reflected in the current and future patterns, and so risk in areas with historically no/low amounts of fire may actually increase (Flannigan *et al.* 2009; Wang *et al.* 2015; Flannigan *et al.* 2016).

4.1.6   Comparison of Results with Previous Studies

Direct comparison of the main results of this study (i.e. the amount of interface area across Canada) with other studies cannot be performed for two reasons; 1) most studies were performed in other areas of the world, and 2) the methods and input data used vary between studies. However, to provide some reference for comparison, the overall results of the national WUI area will be compared with other national studies. Only WUI will be discussed since there are no other studies that investigate the WII or the infrastructure interface (though Caballero *et al.* (2007) and Modugno *et al.* (2016) did include some industrial structures in their studies). Not all WUI mapping studies which defined the WUI (included in Table 1-1) actually produced area estimates, so few studies will be discussed. Additionally, some studies included in Table 1-1 may have produced area estimates for small study areas; only larger-scale studies will be compared here.

Most studies that calculated the area of the WUI were done in the United States, with six studies producing a national estimate for the conterminous United States. From these studies, the total WUI area range drastically, from 39.8 million ha to 87.1 million ha (covering about 5 to 11% of land area). Specifically, the area of the conterminous United States that was defined as WUI for each study was: 39.8 million ha (5% of land area) (Menakis *et al.* 2000), 71.9 million ha (9%) (Radeloff *et al.* 2005), 46.6 million ha (6%) (Theobald and Romme 2007), 84.8 million ha (11%) (Haas *et al.* 2013), 87.1 million ha (11%) (Tully 2013), and 71.9 million ha (9%) (Thomas and Butry 2014). In contrast, this study found there is 32.3 million ha of WUI in

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[10] *Several studies actually define fire risk as just fire occurrence risk, neglecting the full definition of risk (e.g. Haight et al. 2004, Lampin-Maillet et al. 2010).*

Canada covering 3.8% of the land area. Disregarding differences in methodology, it appears WUI in Canada does cover a smaller area and proportion of the country compared to WUI in the United States.

Modugno *et al.* (2016) studied WUI in European countries. Total areas of WUI were not provided, but percentages of each country covered by WUI ranged from 0.1% to 17.4%, with an average of 3.5% (standard deviation 3.6%). Putting aside differing methods between the Modugno *et al.* (2016) study and the current study, Canada has a similar percentage of land mapped as WUI (3.8%). In particular, Canada has a similar percentage of WUI as Slovenia (~3.5%), Hungary (~3.6%), Portugal (~3.7%), Slovakia (~3.7%), and France (~3.8%).

Gowman (2013) mapped WUI in Ontario using differing data and somewhat differing methods to the present study, and found there is 9.0 million ha of WUI which covers 11.5% of burnable land. The present study found 5.9 million ha of WUI, covering 7.3% of burnable land in Ontario. These results would not be expected to be the same, since differing data and methods were used. However, the results are at least within the same order of magnitude, indicating that varying approaches have the potential to produce similar results.

McGee *et al.* (2014) did not map WUI area, but did produce a map somewhat similar to Figure 3-15 in this study (McGee *et al.* 2014 p. 38 Figure 3.2). Both maps use the "Populated Places" dataset and produce similar outcomes. McGee *et al.* (2014) mapped the populated places which have at least 20% forest cover within a 2.4 km buffer, using a coarse scale forest region map. To produce Figure 3-15 in this study, actual WUI areas of forested land were used instead of all forested regions, and a larger 5 km buffer with at least 500 ha of WUI was required to classify the location as one with substantial amounts of WUI.

4.2   Applications

The results of this study, including the interface maps themselves, may be used for research purposes (future research directions are discussed in section 5.1), but also in a wide variety of practical applications. Applications discussed in this section include various applications within wildfire mitigation planning, long-term planning, and decision support. As discussed in section 2.4, care must be taken when using these interface maps to use them in an appropriate manner at an appropriate scale. As mentioned in section 2.4, these maps are not intended for use at a small scale, i.e. structure scale or small neighbourhood/community scale.

All practical applications of these maps should take into account the limitations of the input data, and only be used as one tool among other information sources for high-level decision making.

4.2.1 *Wildfire Mitigation Planning Applications*

Wildfire mitigation planning applications include FireSmart activities, fuel treatments, building codes, municipal bylaws, industrial fire mitigation regulations, and infrastructure fire mitigation. FireSmart and other mitigation activities done by homeowners or municipalities could be informed by the results of this study. FireSmart was first released in 1999 and includes a set of voluntary guidelines for primarily homeowners to reduce wildfire risk to their home, such as using fire-resistant building materials or removing wood piles or dead vegetation from the area surrounding your home (Partners in Protection 2003). The interface maps produced here could be used when focusing priority locations for FireSmart awareness or public engagement or education campaigns as suggested in McGee (2011), McCaffrey *et al.* (2012), and Haas *et al.* (2013). The maps could be used to decide what districts or communities to prioritize when allocating funds or targeting FireSmart community initiatives. For example, if a certain region has a very high amount of interface, perhaps those areas would be prioritized over areas with much less interface area. The maps could also be used as a tool to encourage homeowners to take action to reduce their fire risk by following FireSmart recommendations. If a neighbourhood is shown on the interface maps as adjacent to large areas of interface, showing homeowners where the interface areas are (at a community or district level) may be a way to communicate the potential risks of fire. However, homeowners completing mitigation activities is a complex issue, with perceived risk being only one element in homeowner decisions to mitigate wildfire threat (as discussed in Winter and Fried (2000), McGee (2007), Mell *et al.* (2010), and McFarlane *et al.* (2011)). Despite their beneficial and practical applications to community fire mitigation, using spatial maps of interface areas could actually be detrimental to a community's fire mitigation initiatives. For example if a homeowner sees their house on a map and it is not zoned as interface, then convincing them to take action to mitigate fire effects would be challenging, despite the fact they may still be at risk. However, as mentioned previously (sections 2.4 and 4.2), these maps should not be used at the scale of individual homes.

In a similar fashion to FireSmart activities, targeting fuel treatment activities would also benefit from the use of these interface maps at a coarse scale (i.e. between communities/regions).

Fuel treatments are a component of FireSmart, but can be extended to lands beyond those immediately surrounding structures and communities. Fuel treatments often focus on fuel reduction or modification (through prescribed burning or mechanical thinning/fuel modification) to reduce fire hazard and spread potential or to make firefighting activities more safe and effective (Partners in Protection 2003; Mell *et al.* 2010; Bar-Massada *et al.* 2014). The effectiveness and details (i.e. treatment type, re-treatment period, treatment size) of fuel treatments is still subject to debate (Cohen 2000; Theobald and Romme 2007; Beverly *et al.* 2009; Mell *et al.* 2010; Beverly and Bothwell 2011; Calkin *et al.* 2014), as fuel treatments will not necessarily stop fires with extreme fire behaviour under extreme fire weather conditions (Cohen 2000; Calkin *et al.* 2014). Despite the continued research into fuel treatment methods and effectiveness, the interface maps produced here could be used to better focus the fuel treatment activities so they are located in communities or regions with more potential for interface fires. Fuel treatments are generally more effective when focused closer to communities (Cohen 2000), though often they are not, due to land ownership restrictions (Schoennagel *et al.* 2009). If these maps are used to prioritize communities or regions which should receive fuel treatments, ancillary data at a fine scale should be used to determine the actual locations and characteristics of the fuel treatments to maximize effectiveness (Theobald and Romme 2007; Beverly *et al.* 2010), and could ideally be placed closer than the maximum buffer distance used here (i.e. 2400 m).

Building codes, municipal bylaws, and zoning can be put in place by municipalities to reduce a community's susceptibility to wildland fire. These interface maps could be used to target these initiatives to areas with extensive interface area. Building codes for new or existing structures can mandate use of fire-resistant materials and bylaws could require the clearing of flammable vegetation from around structures in areas with lots of interface area (Peter *et al.* 2006; Alexandre *et al.* 2014). Bylaws could be taken even further, with the introduction of laws at provincial or national level. Examples of this are found in France and parts of Spain where a mandatory 50-100 m radius around structures which are < 200 m (France) or < 400 m (Spain) from wildland fuels must be cleared by homeowners (Lampin-Maillet *et al.* 2010; Chas-Amil *et al.* 2013). Insurance companies can also encourage these mitigation activities through rebates or new rate categories for compliant homeowners. Additionally, municipalities can limit new

development in areas that would dramatically increase interface area through appropriate zoning (Winter and Fried 2000; McGee 2007).

In addition to community applications, there are specific industrial applications from this study, since WII maps were produced. Most industrial operations are subject to provincial operating regulations, which generally require fire suppression capacity, fuel breaks, and fire planning; for example, Ontario has the Forest Fire Prevention Act (Province of Ontario 1990), and Alberta has the Forest and Prairie Protection Act (Province of Alberta 1972). The WII maps, together with WUI and infrastructure interface maps produced here could be used to identify areas of concern which may require additional regulations to mitigate wildland fire. The WII map may also be used by industry members to identify problem areas and proactively improve mitigation activities to protect their workers, equipment, and production capacity.

The infrastructure interface maps also have applications to wildland fire mitigation. For example, fuel reduction activities already occur under powerlines, around gas lines, and next to railways. However, in areas mapped with larger areas of infrastructure interface, or areas where infrastructure interface is nearby large areas of WUI, perhaps additional or more frequent fuel removal should be performed. The infrastructure interface maps could also be applied to fire preparedness plans for powerlines, gas lines, and railways. These plans include shutting off powerlines and gas lines and halting rail services when a wildfire is in the area, and could be improved with additional spatial information such as the infrastructure interface maps. Furthermore, with regards to railway fire mitigation, the infrastructure interface maps (along with WUI and WII maps) could be used to help with selecting what areas should receive extra fire suppression effort when performing rail grinding activities (which produces the potential for many ignitions along the railway; Grunstra and Martell (2014)). In extreme fire weather situations, railways may want to avoid grinding in certain areas with large interface areas.

4.2.2 Long-term Planning Applications

Long-term planning applications of the interface maps produced in this study include applications within city planning, fire management planning, evacuation planning, and wildfire insurance. City planning of new development or of communities rebuilding post-burn can benefit from the use of the information in this study, and are potentially even more important in regions or communities shown on the maps here with high amounts of interface areas. For example,

planning parks or golf courses at the edges of interface neighborhoods can be part of strategic plans to increase the distance between wildland fuel and structures (Moritz and Stephens 2008). As suggested by multiple authors (Moritz and Stephens 2008; Lampin-Maillet *et al.* 2010; Price and Bradstock 2014; Fox *et al.* 2015), another strategic planning concept for new developments is to increase structure densities of areas that are already classified as interface (i.e. "infill development" as opposed to "leapfrog development"), to lessen the growth of the interface and make those areas more easily defensible. These higher density interface areas have less risk of wildfire due to less wildland vegetation cover (Price and Bradstock 2014), see comparatively smaller increases in fire suppression costs compared to structures built in more isolated locations (Gude *et al.* 2013), and generally see a decrease in the probability that a structure may be damaged or destroyed by fire (Syphard *et al.* 2012). Communities may also want to consider that community shape (and the resultant interface shape) can result in higher fire exposure potential, as found in (Beverly *et al.* 2010). For example, a community with a round shape has a smaller perimeter/area ratio as compared to a community with an elongated shape or with multiple "peninsulas" of development jutting out from the community. The smaller perimeter/area ratio can result in a smaller interface area and thus lower overall risk to the community. Planning in areas classified as interface should also accommodate evacuation routes, easy access for firefighting equipment, and access to suppression equipment (e.g. hydrants) (Moritz and Stephens 2008; Haas *et al.* 2013). Rebuilding communities after destruction by fire permits a unique chance to improve upon structure location characteristics that may have led to structure vulnerability; however it appears most rebuilding fails to adjust development accordingly (Alexandre *et al.* 2014). Despite this trend, this map could be used to help inform placement and characteristics of future rebuilding efforts.

Fire suppression and management planning can benefit from the results of this study as well. Knowing the location and extent of the interface is useful information for planning for hiring, purchasing, community outreach programs, and budgeting. Cost estimates of protecting the interface would also be useful (Mell *et al.* 2010), and this map would form the first step required for this analysis, and in fact just having the current area of interface numbers for Canada and for each province is useful information for justifying fire management expenditures. Some studies have looked at interface (specifically WUI) suppression costs. In general, suppression is more expensive in the WUI, and is particularly expensive in sparsely populated areas (Canadian

Council of Forest Ministers 2005; Peter *et al.* 2006; Gude *et al.* 2013). Fire management agencies can use this map (and the upcoming research on change detection in the interface that will be discussed in section 5.1) to justify the need for monetary support for fire management, mitigation, and suppression. Suppression costs are expected to increase drastically in Canada, with the potential for current fire management to be overwhelmed by climate change effects on fires (Podur and Wotton 2010; Hope *et al.* 2016).

Evacuation planning or modelling would benefit from the use of the interface maps, but this is a complex problem and would require much more information than just interface locations. The WUI or WII maps would be useful in this application, but also the infrastructure interface map showing roads which may be escape routes. Areas with a single road out of a community and lots of infrastructure interface surrounding the road could potentially be in a difficult situation in the case of a wildfire forcing an evacuation through direct threat or from smoke effects (Beverly and Bothwell 2011).

Insurance companies may find these interface maps useful. Though this map should not be used to calculate insurance rates for an individual house (the scale is not appropriate for that application), it may be useful to adjust rates based on the amount of interface in a broad area. Wildfire insurance will likely become an even more important issue in the future (Mills 2005), though not everyone fully insures their properties (McGee *et al.* 2014) and insurance in some cases could be less expensive than fire mitigation options (Bradley 1984). Using insurance as encouragement (e.g. through rate rebates for FireSmart activities taken) to make communities, industry, and infrastructure more resilient to fire would likely be an effective risk reduction strategy (Peter *et al.* 2006).

4.2.3 Decision Support Applications

Applications of these interface maps also include a variety of wildfire decision support activities including: resource prepositioning, values protection, fire prioritization, alerts for interface fires, and risk modelling. Use of these interface maps for small-scale decision support is not appropriate due to scale limitations (discussed in section 2.4), but use in broad-scale operational decisions would be beneficial. For example, wildland firefighting equipment and personnel are often prepositioned across a region (in some cases up to hundreds of kilometers from a fire base), based on where hazard or ignition risk is high in an effort to reduce response

time for initial attack (Canadian Council of Forest Ministers 2005). The maps produced in this study could be used to assist in deciding where to preposition resources, by putting highest priority on large areas of interface or high densities of interface which have high fuel hazard and high ignition risk.

Decisions concerning values protection (i.e. direct protection of structures by using sprinklers for example) could also benefit from the use of these interface maps. In the event of a fire threatening a specific interface area or multiple areas, having the knowledge of how much interface area require protection would be very useful when deciding how many values protection kits (sprinklers, pumps etc.) or crews to dispatch.

When multiple fires are occurring at once in a given region, fire prioritization is an important decision support aspect. Choosing what fires to send resources to (and additionally what type of resources and how many) could benefit from the information on these interface maps by providing interface areas near the fires or in the path of the fires. Current fire behaviour, weather, forecasted weather and many other factors would also need to be taken into account, but the interface map would provide an additional tool to help make these difficult decisions.

Another possible application of these interface maps for fire decision support is when a fire is reported to a fire management agency, the fire location could trigger an "interface fire" warning if it is within or near an interface area. This warning would provide instant information for decision makers and could improve on existing systems which rely on values maps. An interface fire typically receives fire suppression and may also require evacuations, so advance warning would be useful. Concerning evacuations, the interface maps could also be combined with escape route capacity to trigger alerts that evacuations may be required (as discussed in Haight *et al.* (2004) and Haas *et al.* (2013)).

Incorporating the interface maps into a fire occurrence or risk assessment study is another potential application of the results of this study which would be useful for fire decision support activities. Fire occurrence modelling would benefit from use of the interface maps from a perspective that the increased human activities within the interface would impart increased ignition risk due to human-caused ignitions. Any application that would find use in having interface areas mapped would likely also have use for interface fire areas with risk incorporated into the maps. The following section on "Future Research" (section 5.1) will discuss this topic further.

5   CONCLUSION

In this study, the primary goal was achieved, which was to produce three national interface maps: one for the traditional wildland-urban interface (WUI), another for the wildland-industrial interface (WII), and a third for the infrastructure interface. These interface maps are available within this document as national maps (Figure 3-1, Figure 3-3, Figure 3-4, Figure 3-5) and provincial or territorial maps (Appendix 2). The maps are also available by request as the full resolution raster layers for scales from small study areas to the full national area.

The interface maps in this study were produced using the intersection of variable-width buffers around values (i.e. structures or vulnerable infrastructure) with burnable fuel areas. The areas mapped as interface represent the fuel area that is considered to be close enough to a value to potentially put that value at risk in the case of a wildland fire. The fuel area mapped as interface may require full fire suppression and/or fuel treatment, and the values themselves would likely require values protection and fire mitigation measures to be taken to protect the values. The interface maps do not incorporate all fire risk factors (e.g. fire weather, fire hazard, structure vulnerability, potential losses etc.), and is not intended as an indication of risk, but does show the areas which (under appropriate conditions in the event of a fire) could potentially be destroyed by wildland fire.

In addition to the interface maps, information and statistics were produced in this study concerning the interface areas directly, or the relationships between interface areas and fuels, structures, and past fires. In summary, in Canada it was found that there is 32.3 million ha of WUI (covering 3.8% of land, or 5.8% of burnable fuel area), 10.5 million ha of WII (covering 1.2% of land, or 1.9% of burnable fuel area), and 109.8 million ha of infrastructure interface (covering 13.0% of land, or 19.5% of burnable fuel area). In general, Quebec, Ontario, Alberta, and British Columbia have the largest areas of interface for each of the three types of interface, but three eastern provinces (Nova Scotia, New Brunswick, and Prince Edward Island) have the highest densities of interface. Fuels are generally of "higher hazard" (i.e. those with greater suppression difficulty; see section 3.3.1 for full definition) within interface areas compared to outside interface areas; so firefighting is typically more challenging in those "higher hazard" interface areas. More fire area of past fires (from 1980-2014) is found outside interface areas than inside interface areas, likely due to early detection and aggressive fire suppression within

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interface areas. Overall, many past fires have occurred within what are currently mapped as interface areas (at least for a portion of their burned area), with 17% of fire polygons within WUI areas, 6% within WII areas, and 38% within infrastructure interface areas.

This study provides the first high-resolution maps of interface areas in Canada. Previously, no data was available on this topic at the national level[11] and forms the first step to studying, mitigating, and managing fires within interface areas. The novel topics of the WII and infrastructure interface maps were presented in this study, and provides the first national maps (for anywhere in the world) focusing on these important interface types. For all three interface types, these maps represent an initial effort to map the national interface area for Canada. In the future, these maps will require updates and improvements. Updates for the fuels data is crucial since these data are already out of date (see section 2.1); ideally a national high-resolution (30 m or better) fuel type map would be used. The structure data from CanVec+ is constantly being updated, and with any updates to the interface maps, the newest version of the dataset will be used. Furthermore, as additional data becomes available (e.g. more detailed fuels information such as fuel loadings or seasonality), these maps can be improved dramatically. The general interface mapping methods outlined here (i.e. a fuels-based mapping approach using a variable-width buffer; details in sections 2.2 to 2.3) are also useful at smaller scales than the national approach used here and can be used in further studies of interface areas.

The results of this study provide a baseline for future research (e.g. risk mapping and prediction of future interface areas; will be discussed in section 5.1) but also has a variety of practical applications (e.g. various applications within wildfire mitigation, long-term planning, and wildfire decision support; were discussed in section 4.2).

5.1   Future Research

There are two primary topics of research based on these interface maps that will be pursued in the near future. The first is an investigation of fire risk in the interface. For an initial look at interface fire risk, existing spatial products will be used to build a risk map of the interface. These existing products are readily available for fire management operations on a national scale and include maps from the Canadian Wildland Fire Information System (e.g. a fire danger map, fire weather map, lightning ignition map, fuel moisture maps) and also a fire regime

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[11] *Though Taylor et al. (2014) did produce a coarse-scale assessment of national WUI at the census level; this data is not published.*

map (Boulanger *et al.* 2012) and/or a map of past fires (from the National Fire Database by the Canadian Forest Service (2014)). Though these products combined with the interface map would still not produce a full picture of risk on a national scale, it is an improvement upon the interface map alone being used to approximate risk.

To continue this work on risk, the next step would be to expand the interface map to a full risk model. A multitude of factors would be incorporated, including: fire probability, fuel loads, fuel arrangement, fire behaviour, weather, topography, aspect, socioeconomic variables, structure and property characteristics affecting risk and other relevant factors (as discussed or partially achieved in Menakis *et al.* (2000), Haight *et al.* (2004), Mercer and Prestemon (2005), Hammer *et al.* (2007), Theobald and Romme (2007), Bar-Massada *et al.* (2009), Mell *et al.* (2010), Beverly *et al.* (2009), Haas *et al.* (2013), and Chuvieco *et al.* (2014)). Data availability would severely limit this analysis since the majority of required data is not available (particularly at consistent national scale), but it is possible that in the near future enough data may be available for a smaller spatial area, and a modular overlay approach (as in Lein and Stump (2009)) would allow incremental improvements as more improved data becomes available. The current interface map produced here could also be used to improve this lack of data by focusing data collection on interface areas.

The second topic of future research is to map areas that have seen recent interface area change and then predict future interface areas. Change detection of current interface growth (or possibly decreases in some areas) could be done using remotely sensed images of past structure locations, census data, historical structure data, or coarse scale population maps. WUI change detection studies have been performed in other areas of the world. For example, Hammer *et al.* (2007) looked at three states in the United States and used interpolated census data between 1990 and 2000 to find that overall the three states had an 11% increase in WUI area. Theobald and Romme (2007) used dasymetric mapping of census data along with historic estimates of housing density derived from census data to produce estimates of how much the WUI area has changed from 1970 to 2000 for the conterminous United States; they found a 52% increase in WUI area had occurred. Similarly, Tully (2013) used dasymetric mapping of 2000 and 2010 census data to do a change detection of the conterminous United States and found that a 5.7% increase in WUI had occurred. Fox *et al.* (2015) investigated WUI change in southeast France from 1960-2009

using a structure database and old aerial photos; they generally found decreases in isolated WUI, but increases for more dense WUI areas.

The change detection of the interface in Canada would include recent changes in human population growth, and changes in vegetation cover. Using those rates of change, future interface areas can be forecasted. Changes in fire hazard and risk due to climate change could also be incorporated into the future prediction study. Analysis of this map could look at the causes of the changes (e.g. urban sprawl, increased recreational land use), forecasting the future fire behaviour due to the changes, and providing the amount of change in interface area. The interface area in the future is likely to increase due to changes in human population patterns such as urban sprawl, increased recreational land use, and industrial operations expansion (Bollman and Clemenson 2006; Peter *et al.* 2006; FAO 2007; Liu *et al.* 2007; Theobald and Romme 2007; McGee *et al.* 2014). Fire suppression and mitigation may be able to restrain impacts on structures with this increased WUI area (Fox *et al.* 2015), but eventually the heightened demand on suppression (Podur and Wotton 2010), along with increased fire activity from the effects of climate change (Flannigan *et al.* 2009) will inevitably result in more destructive interface wildfire events.

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Appendix 1: Aggregation Index R Code

Below is the R code created to calculate Aggregation Index (AI) for the fuel raster in this study. See section 2.3.1 for a discussion of AI, along with information on the equations and variables used below.

```r
## Authors: Lynn Johnston and Xianli Wang
## Date: January 2016
## Title: Aggregation Index (AI) calculation


# Load required libraries

library(raster)
library(SDMTools)
library(sp)
library(rgdal)
library(spdep)


# Prepare workspace (clear, set working directory, and redirect the large
temporary files)

rm(list=ls())
setwd("E:/Xianli/people/Lynn")
rasterOptions(tmpdir="E:/RTEMP")


# Call "ClassStat_2.r" function
source("ClassStat_2.r")


# Make list of all input fuel raster files for batch processing and loop
through a defined number of files in batch (5 files in this case)

foo <- list.files("./In",pattern=".tif$")

for (i in 1:5){

  # loads input raster
  r<-raster(paste("./In/",foo[i],sep=""))

  # takes only the required raster values (<10 = burnable wildland fuel ranks
1-5), checks for NA values, assigns non-zero values to a 5x5 matrix
  r2 <- (r<10)
  r2[is.na(r2)] <- 0
  m <- matrix(1, ncol=5, nrow=5)
  m <- m<=1

  # uses the built in "focal" function and the custom "ClassStat_2" function
to calculate AI on a 5x5 matrix moving window. Also logs system time for the
process
```

```r
  system.time(AIMW <- focal(r2, m, fun = ClassStat_2, pad=T,
padValue=0,na.rm=T))

  # creates the "fuelweight" raster by adding the existing fuel ranks (1-5)
to the output AI values (0-2). Assigns 10 (no fuel) to NA cells
  fuelweight <- r + AIMW
  fuelweight[is.na(fuelweight)] <- 10

  # outputs raster result
  writeRaster(fuelweight, paste("./Out/",substr(foo[i],1,nchar(foo[i])-
4),"_out_AIandWeight_xianli_2.tif",sep=""),overwrite=T)
}




# "ClassStat_2" custom function:

ClassStat_2 <- function(mat,cellsize=1,bkgd=0,latlon=FALSE,...) {

  # takes the input matrix ("mat") sent to the function (a 5x5 matrix of
raster cells)
  focal_mat <- matrix(mat,nrow=5,byrow=T)

  # first check to see if centre cell of 5x5 matrix is not 0, then use built
in "PatchStat" function to count number of patches, number of cells, and
number of shared edges
  if (focal_mat[3,3]!=0){

    out.patch = PatchStat(ConnCompLabel(focal_mat),cellsize=1,latlon=F)

    # remove patchID's that are 0 (background 0 values)
    if (0 %in% out.patch$patchID) {out.patch = out.patch[-
which(out.patch$patchID==0),]}

    # calculate AI as in He et al. 2000
    Ai<-sum(out.patch$n.cell)
    eii<-sum(out.patch$n.edges.internal/2)
    n = trunc(sqrt(Ai))
    m = Ai - n^2
    if (m==0) {maxeii = 2*n*(n-1)}
    if (m<=n & m>0) {maxeii = 2*n*(n-1)+2*m-1}
    if (m>n) {maxeii = 2*n*(n-1)+2*m-2}
    AI<-ifelse(maxeii==0,0,(eii/maxeii)*100)
  }else{AI=0}

  # assign coarse category values to AI values and return final values for
output
  # categories: "high" (AI > 90) is assigned 0, "low" (AI between 0-90) is
assigned 1, "zero" (AI = 0) is assigned 2
  # note: 0 AI does not necessairly mean 0 fuel
  AI <- ifelse(AI==0,2,ifelse(AI>90,0,1))
  return(AI)

}
```

Appendix 2: Interface Provincial Maps

This appendix provides provincial or territorial scale maps of interface areas across Canada. These maps do not display the full resolution data, but do provide an additional level of detail over the national maps provided in this study (Figure 3-1, Figure 3-3, Figure 3-4, and Figure 3-5). These maps are for display and informative purposes only. To keep display scales somewhat similar to other parts of the country, Nova Scotia, New Brunswick, and Prince Edward Island are shown together. For each province or territory (or group of provinces) there are three maps: one for the wildland-urban interface (WUI), one for the wildland-industrial interface (WII), and one for the industrial interface. For each province or territory the interface area is provided as total area (ha), as a percentage of land area in that province or territory, and as a percentage of fuel area in that province or territory.
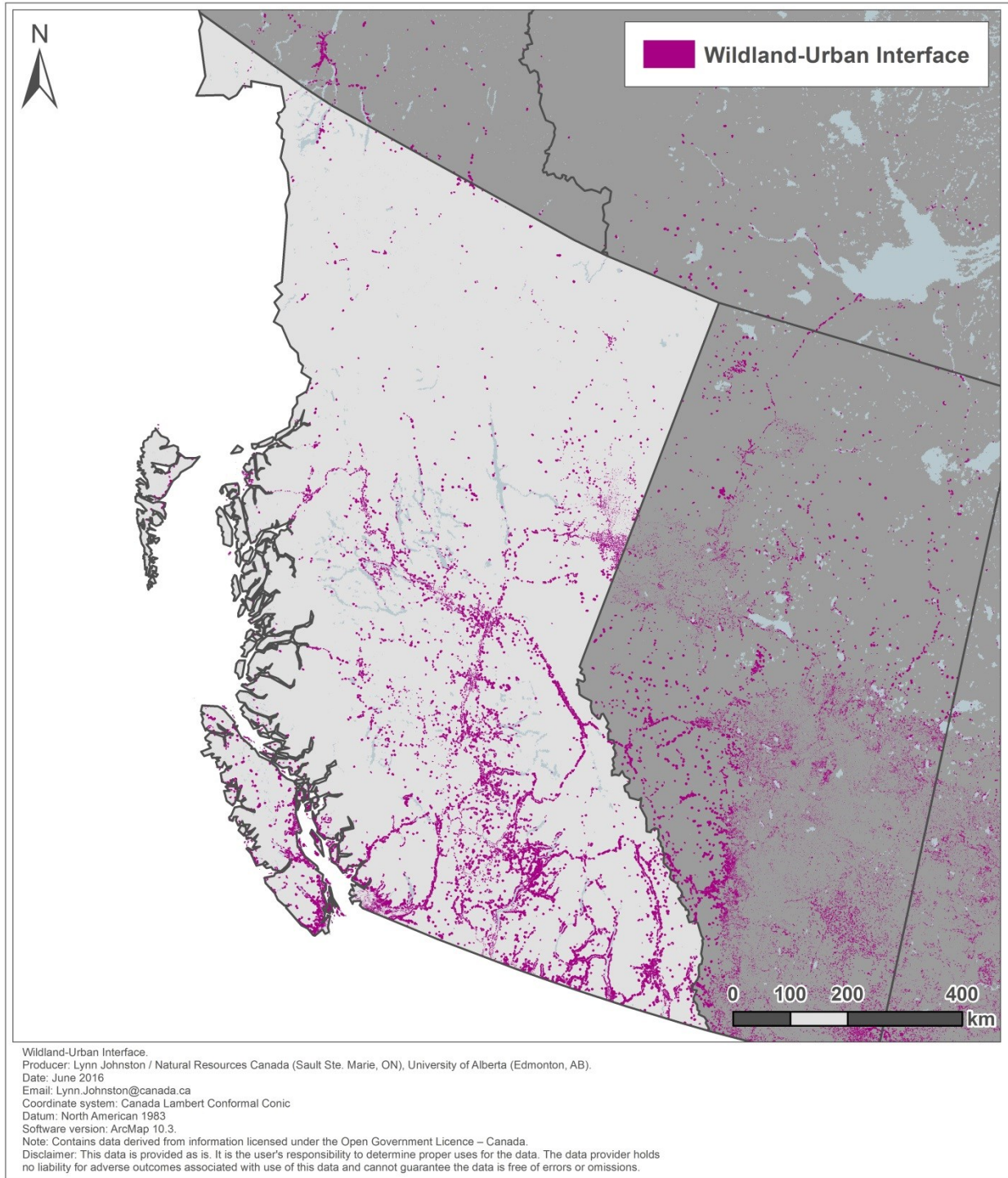
Figure A2-1. Wildland-urban interface map for British Columbia.
Map of wildland-urban interface (WUI) for British Columbia. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 5.52 million ha of WUI in the province, which covers 6.42% of its land area, or 7.77% of its wildland fuel area.
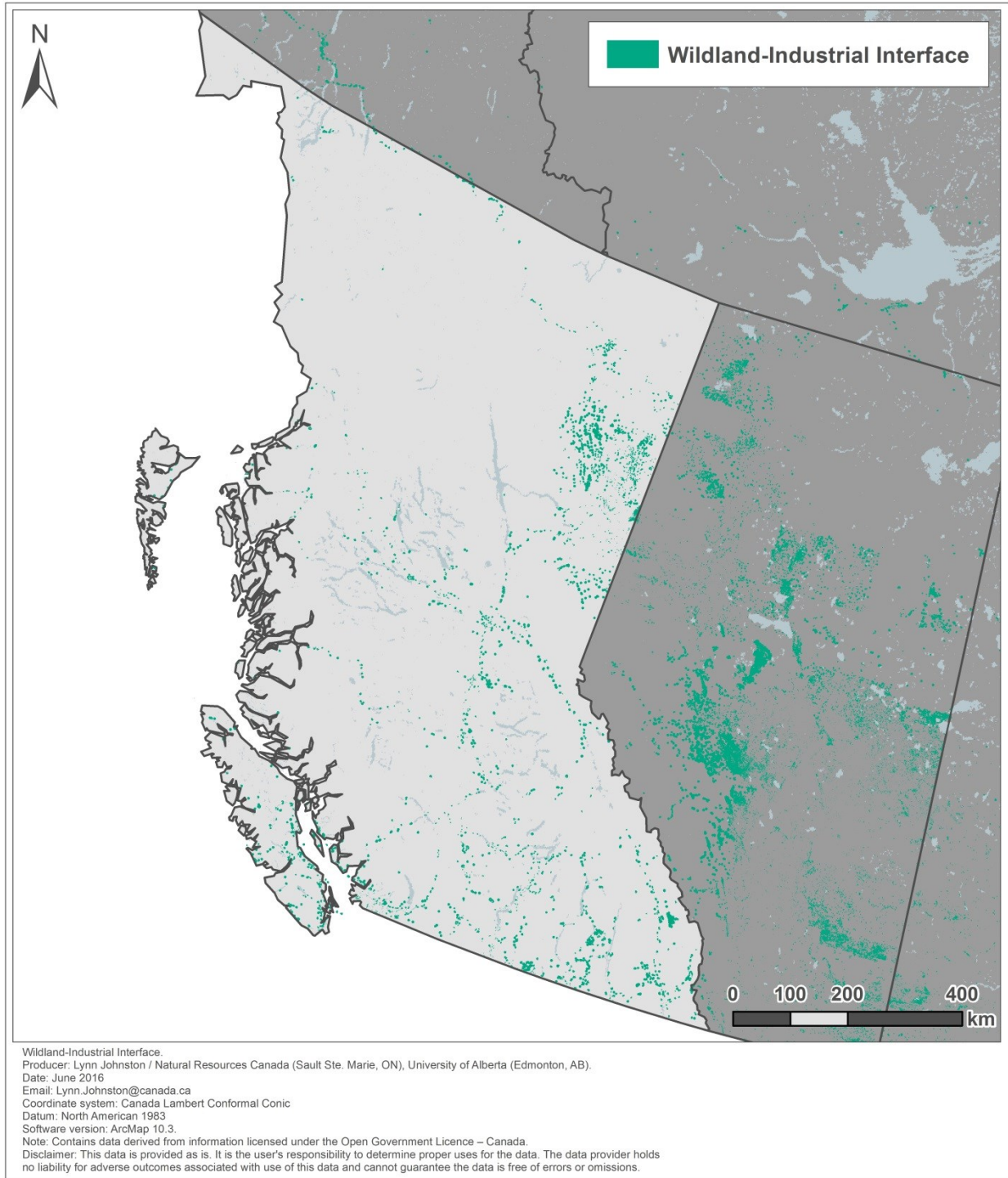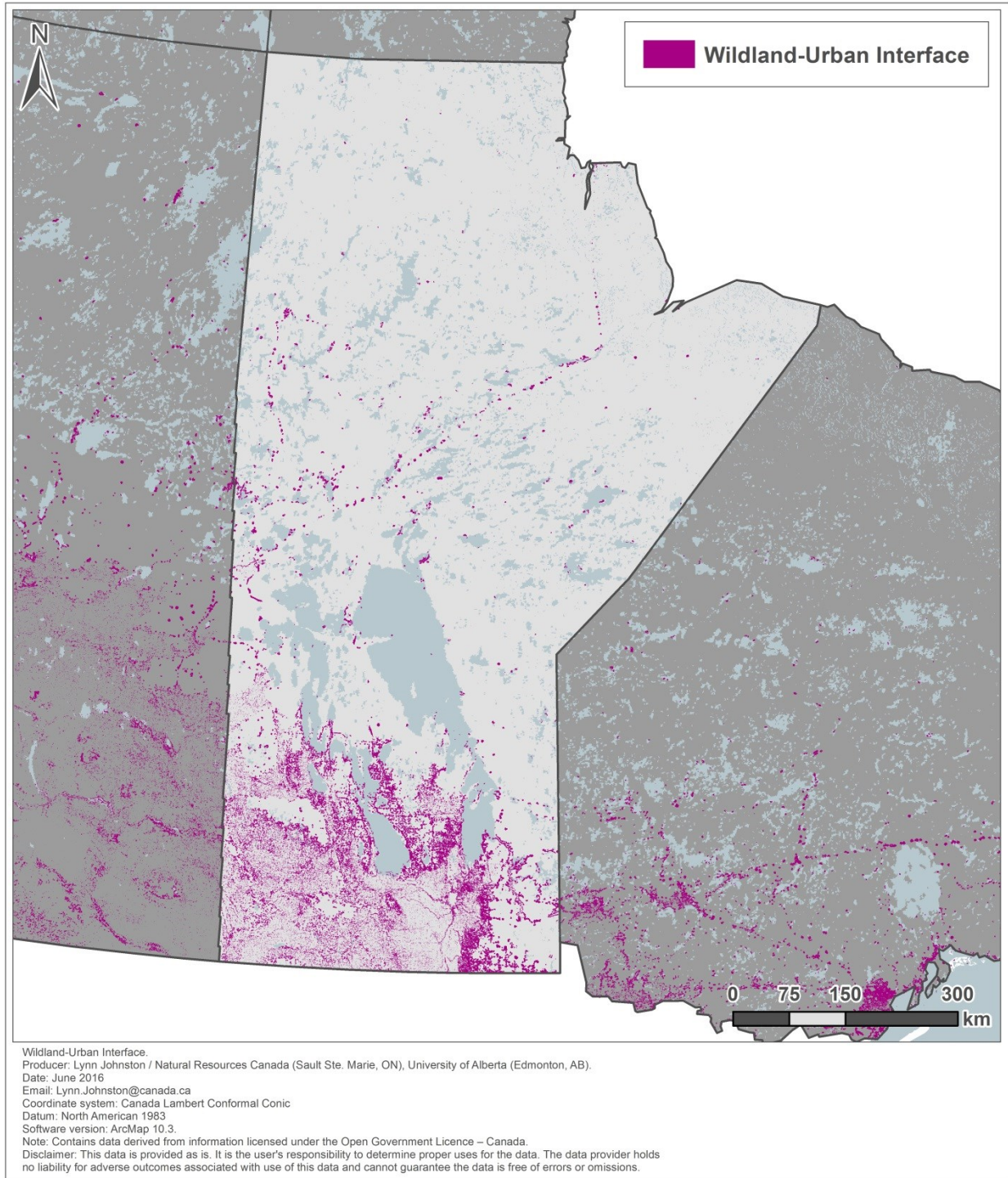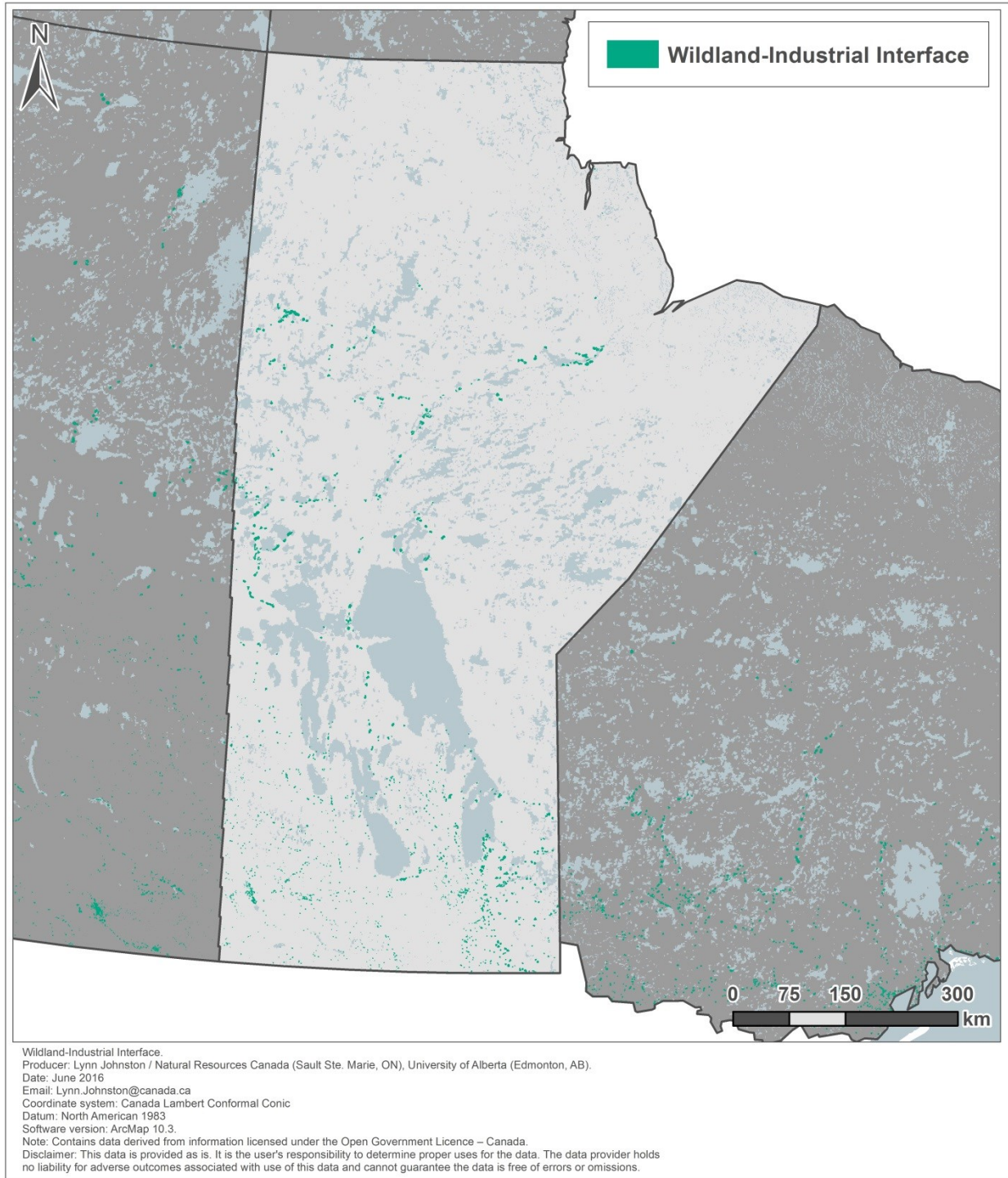
Figure A2-2. Wildland-industrial interface map for British Columbia.
Map of wildland-industrial interface (WII) for British Columbia. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 1.76 million ha of WII in the province, which covers 2.05% of its land area, or 2.48% of its wildland fuel area.
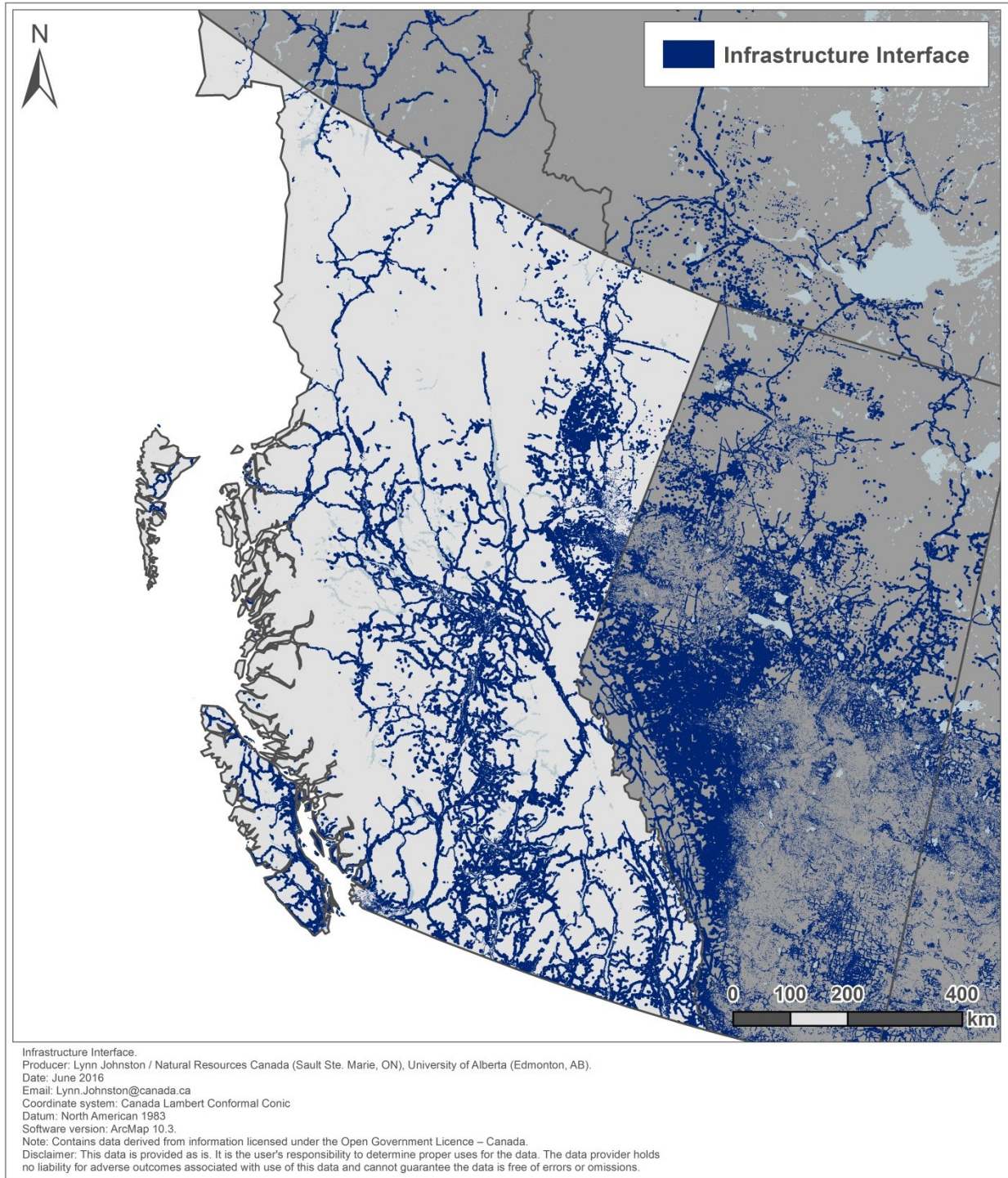
Figure A2-3. Infrastructure interface map for British Columbia.
Map of infrastructure interface for British Columbia. Inland hydrology is light blue, the area of interest is light grey, and the reminder of Canada is dark grey. There are 17.62 million ha of infrastructure interface in the province, which covers 20.49% of its land area, or 24.79% of its wildland fuel area.
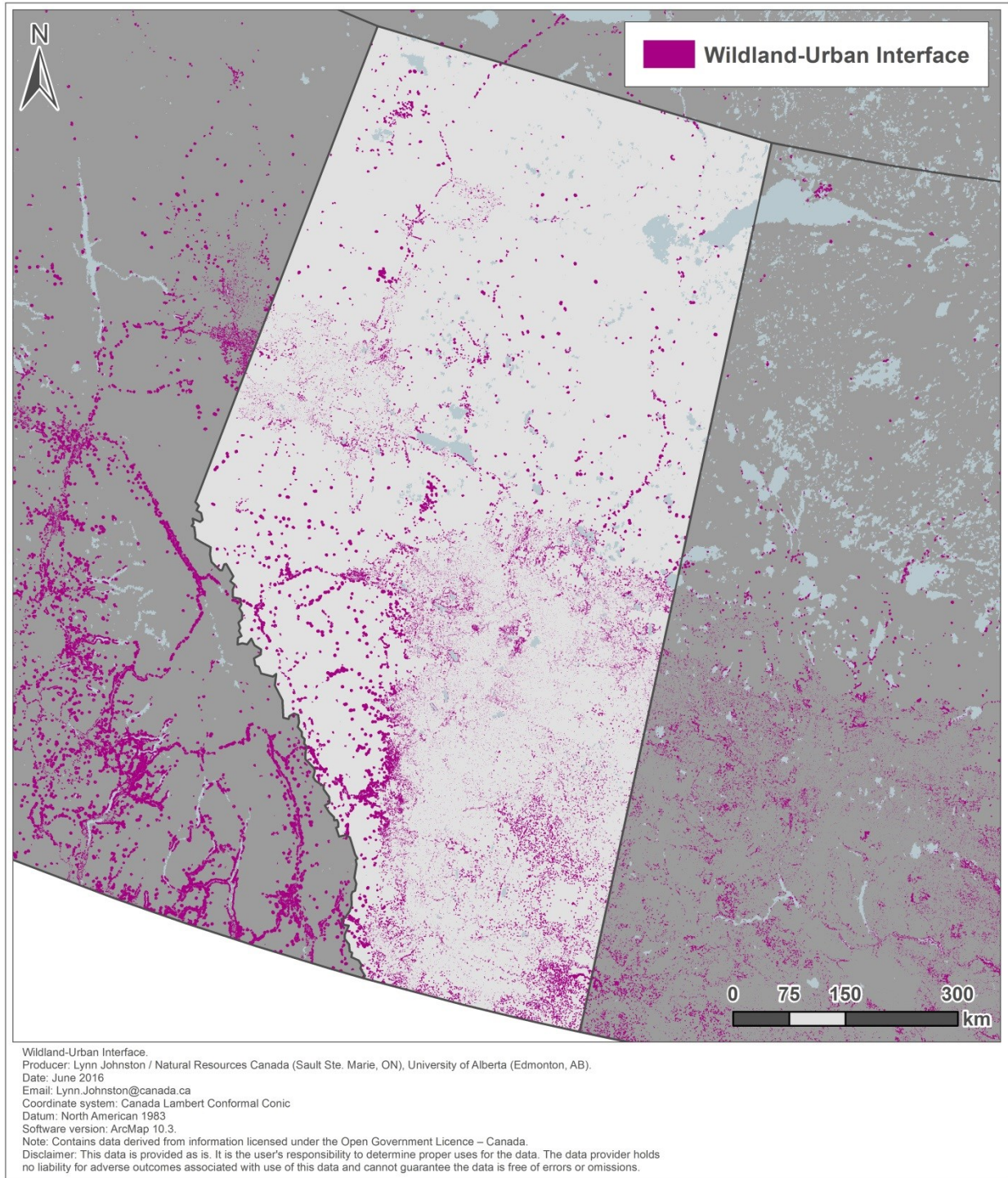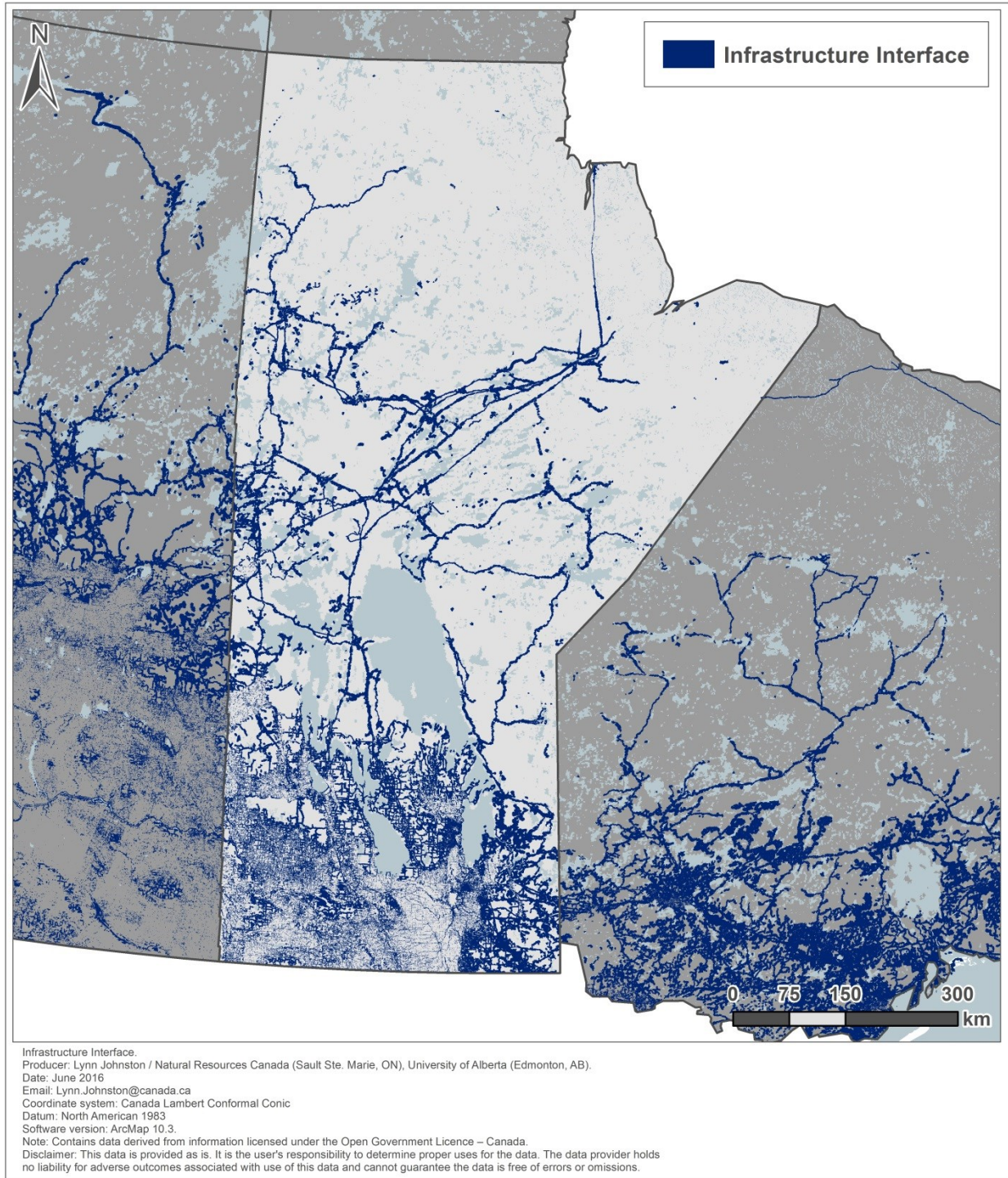
Figure A2-3. Wildland-urban interface map for Alberta.
Map of wildland-urban interface (WUI) for Alberta. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 3.17 million ha of WUI in the province, which covers 5.08% of its land area, or 7.06% of its wildland fuel area.
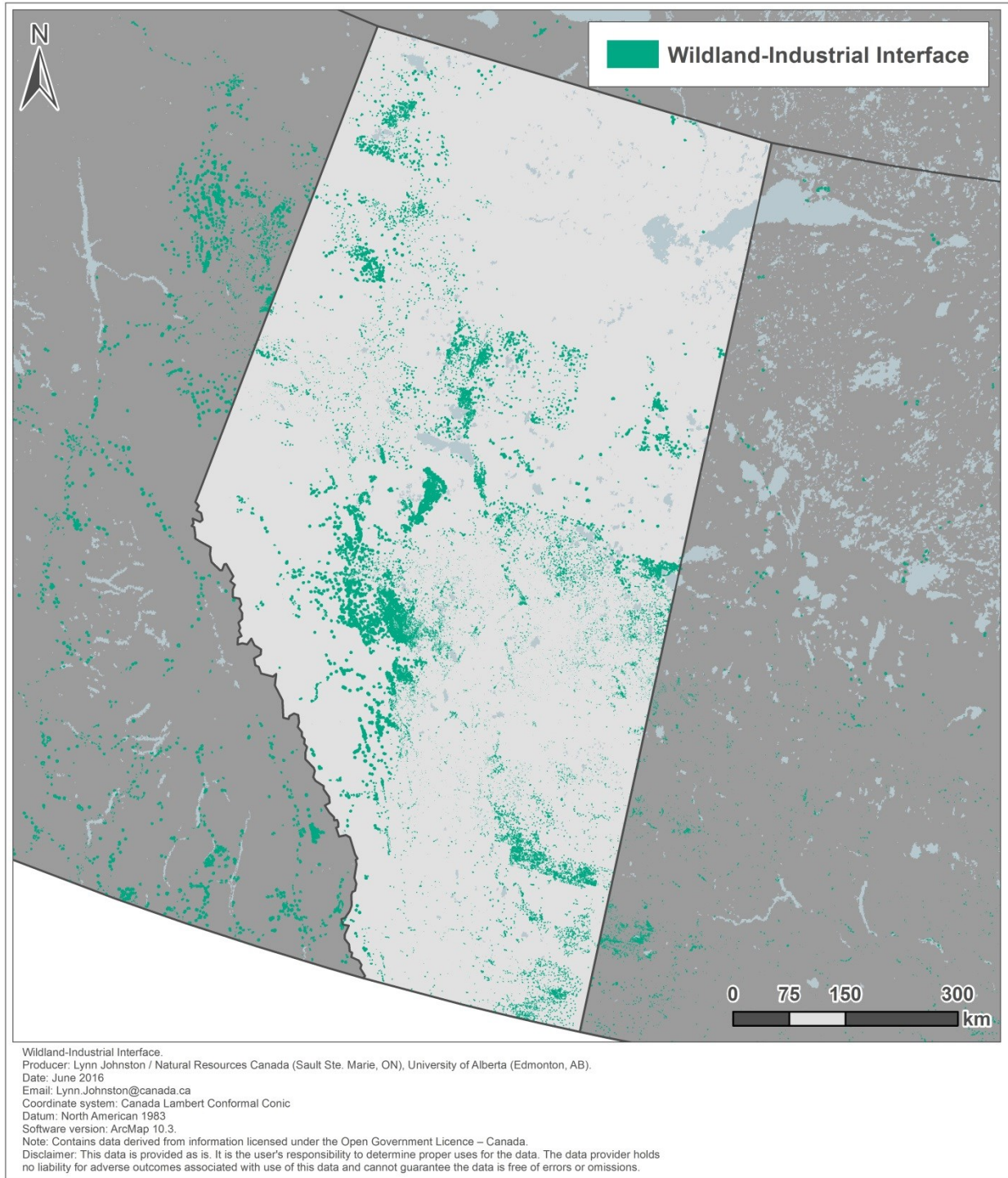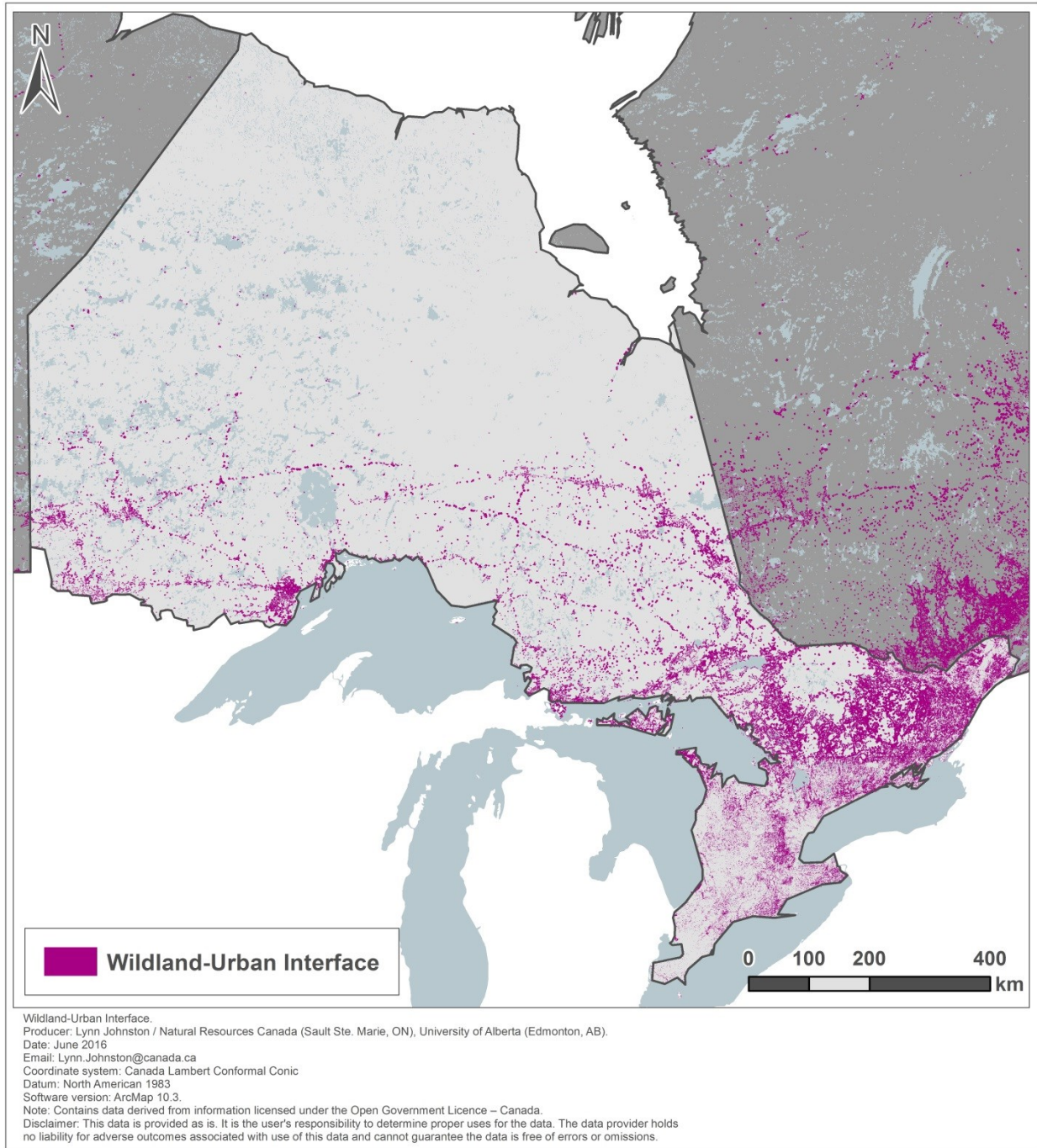
Figure A2-4. Wildland-industrial interface map for Alberta.
Map of wildland-industrial interface (WII) for Alberta. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 3.41 million ha of WII in the province, which covers 5.48% of its land area, or 7.60% of its wildland fuel area.
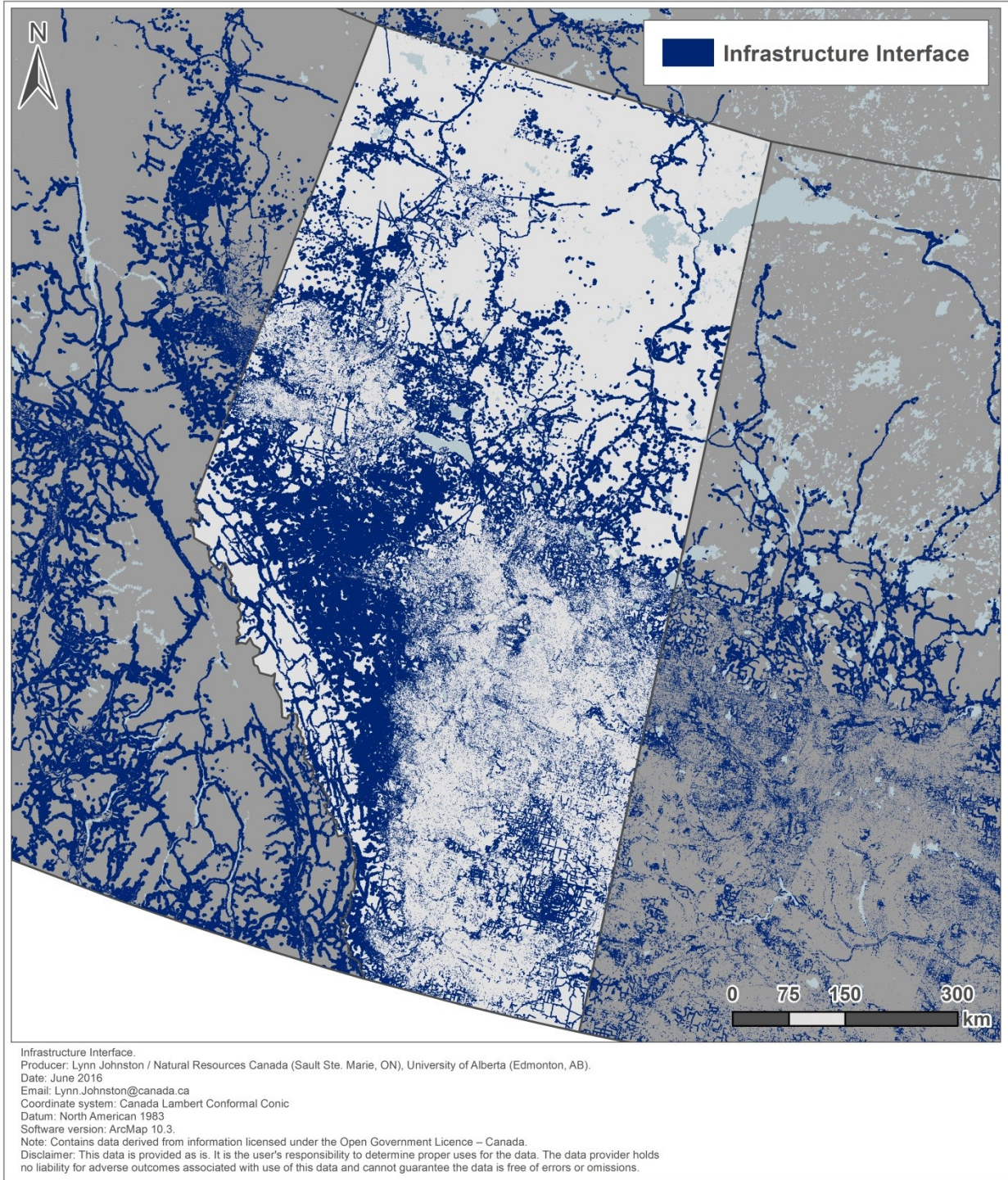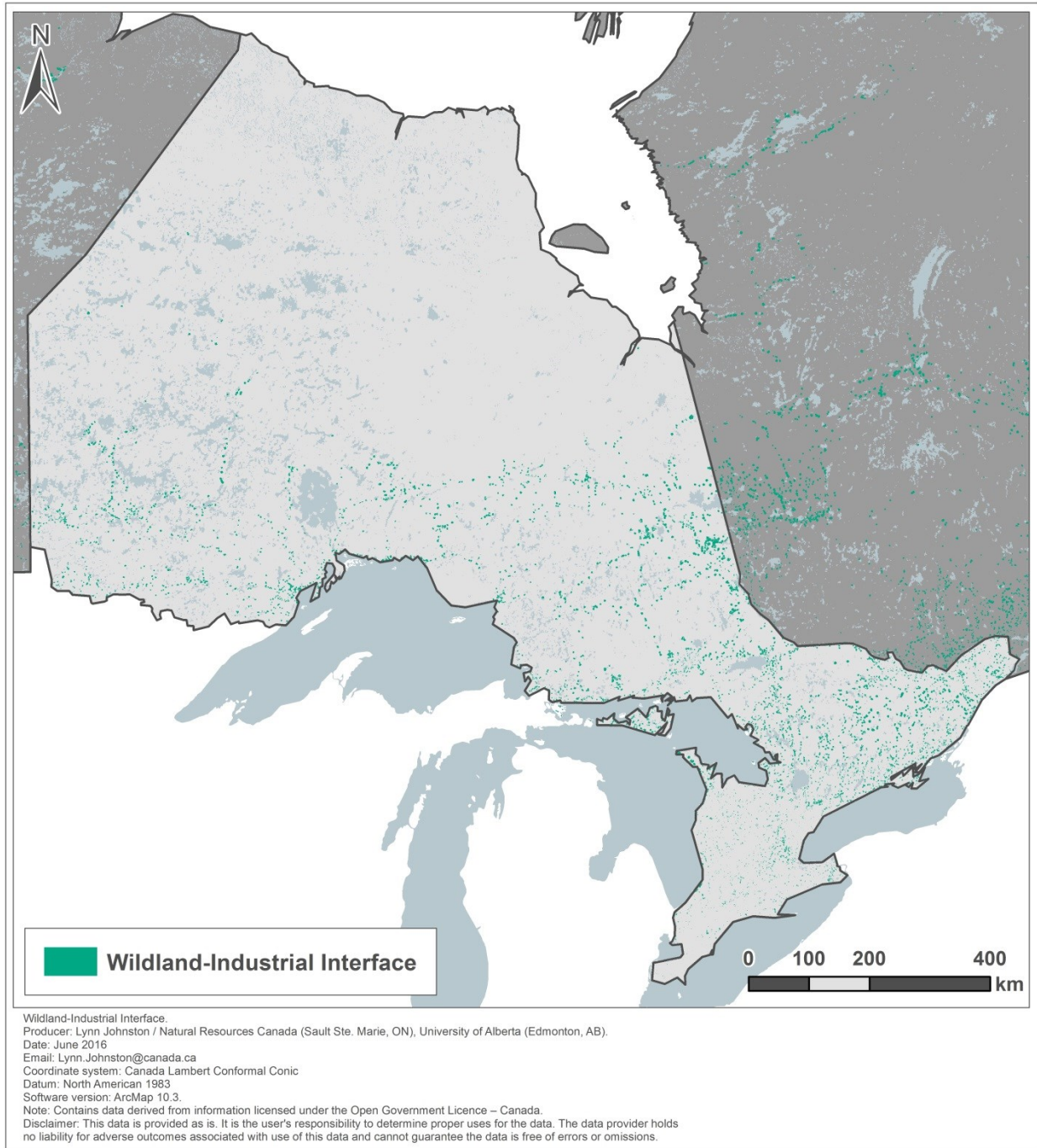
Figure A2-6. Infrastructure interface map for Alberta.
Map of infrastructure interface for Alberta. Inland hydrology is light blue, the area of interest is light grey, and the reminder of Canada is dark grey. There are 18.03 million ha of infrastructure interface in the province, which covers 28.95% of its land area, or 40.18% of its wildland fuel area.
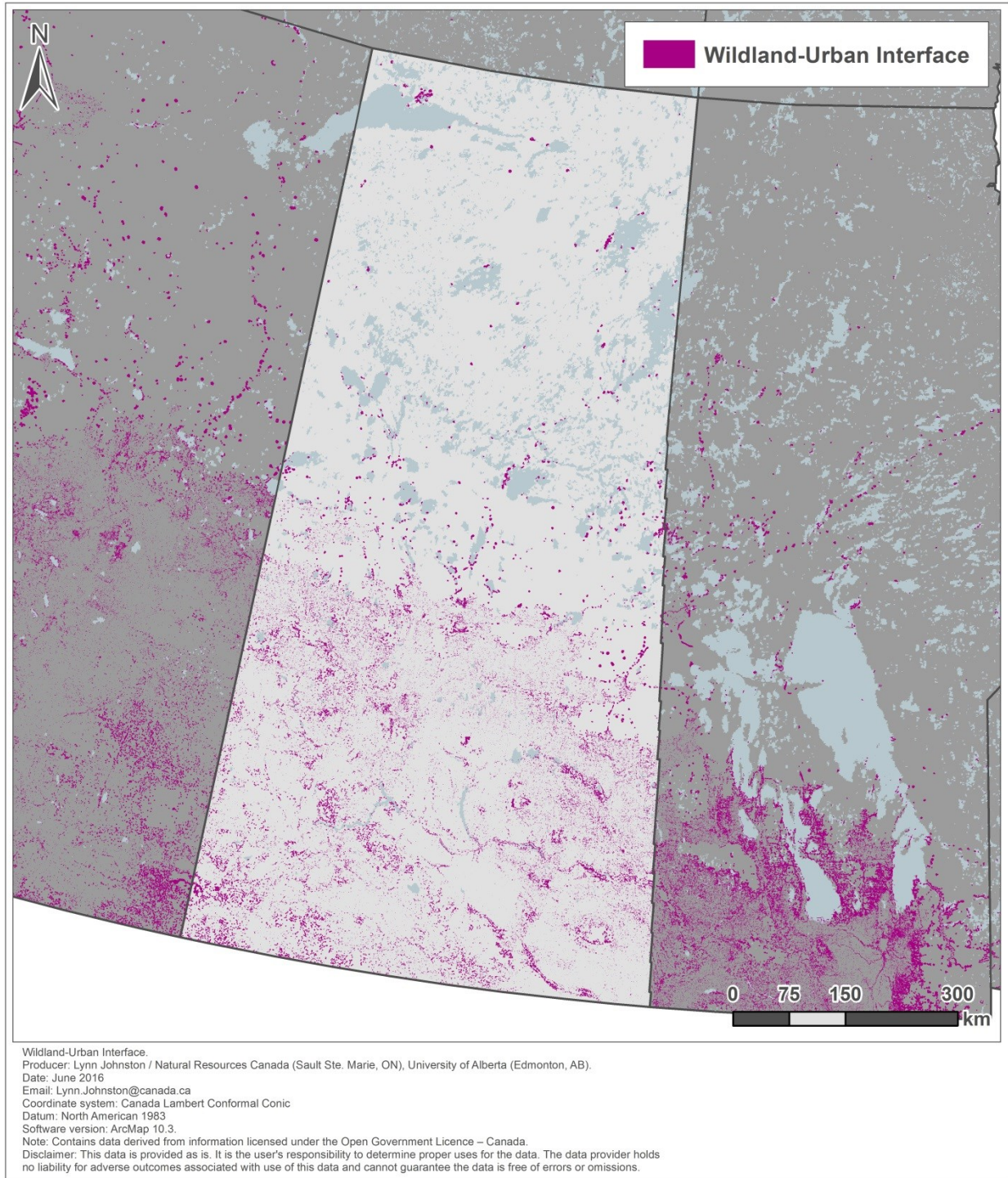
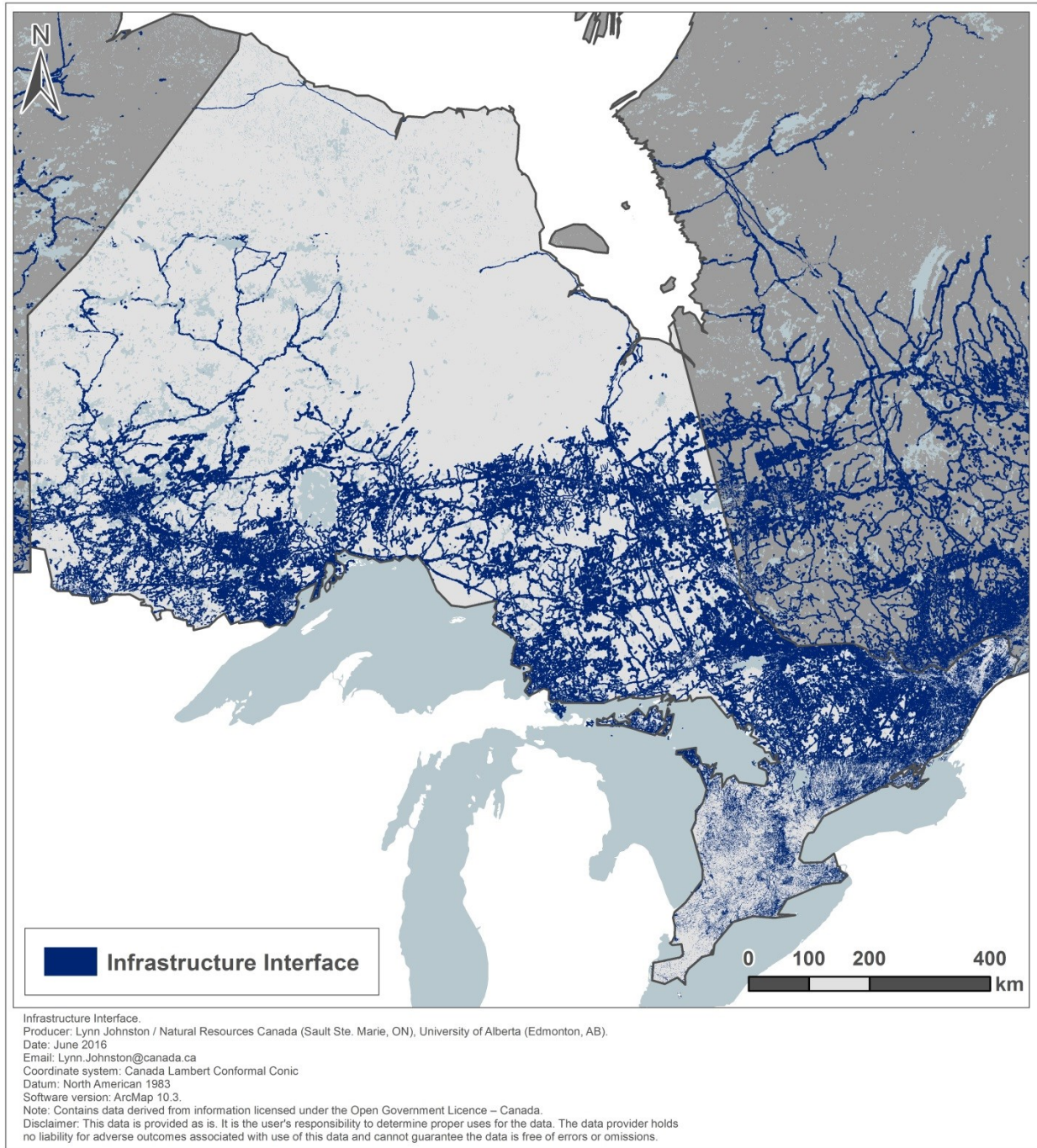**Figure A2-7. Wildland-urban interface map for Saskatchewan.**
Map of wildland-urban interface (WUI) for Saskatchewan. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 1.91 million ha of WUI in the province, which covers 3.32% of its land area, or 5.53% of its wildland fuel area.
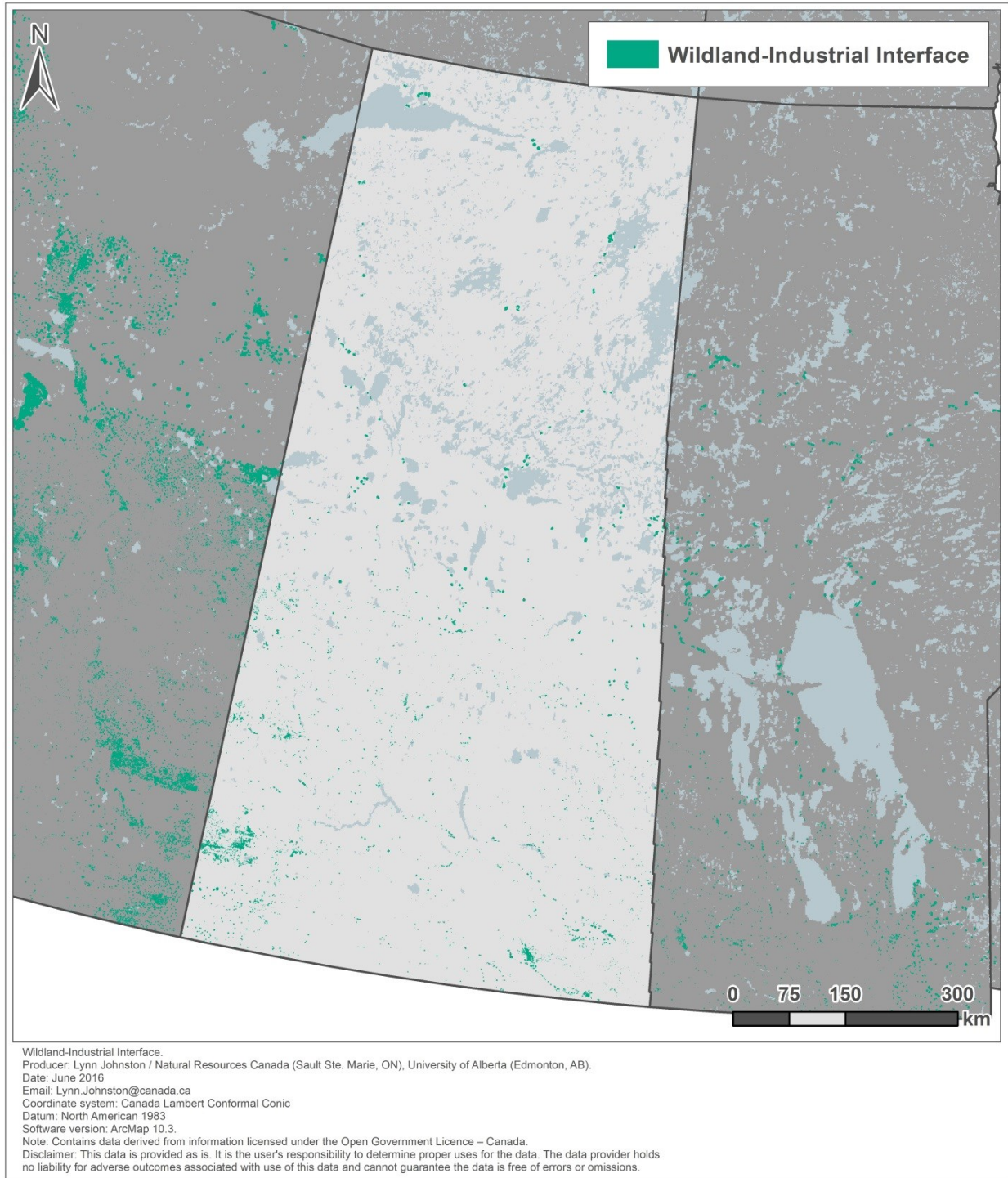
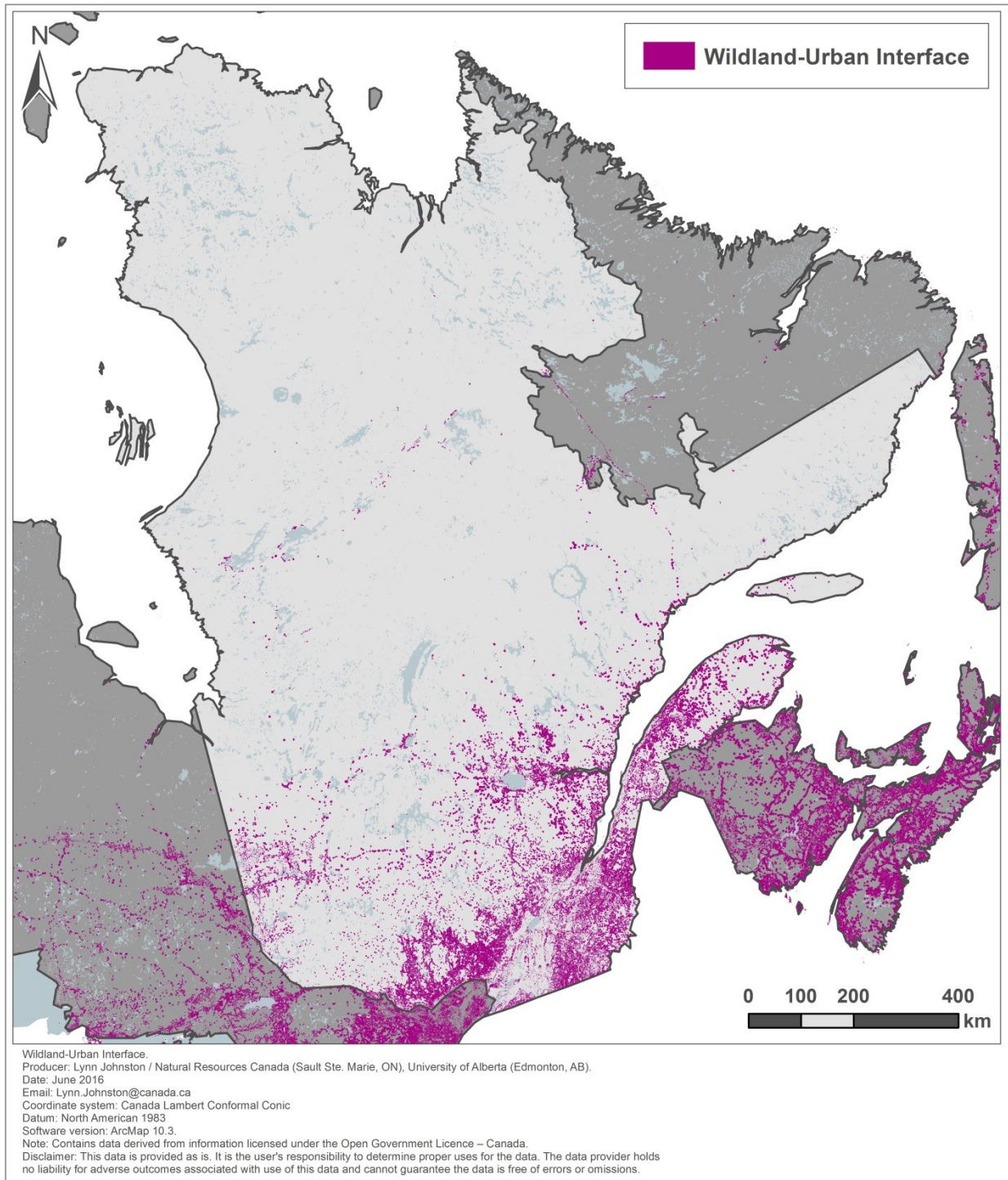**Figure A2-8. Wildland-industrial interface map for Saskatchewan.**
Map of wildland-industrial interface (WII) for Saskatchewan. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 370 thousand ha of WII in the province, which covers 0.64% of its land area, or 1.06% of its wildland fuel area.
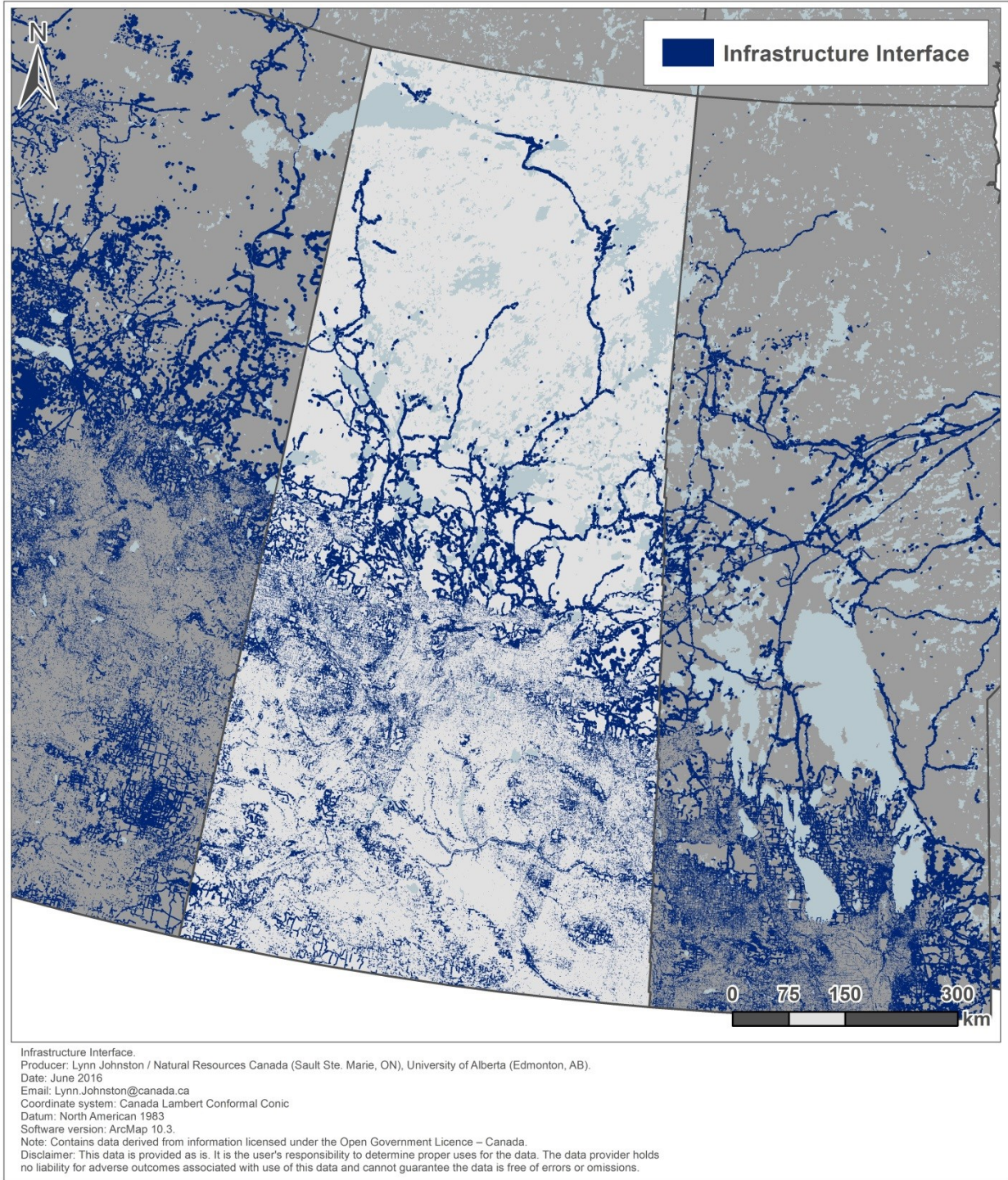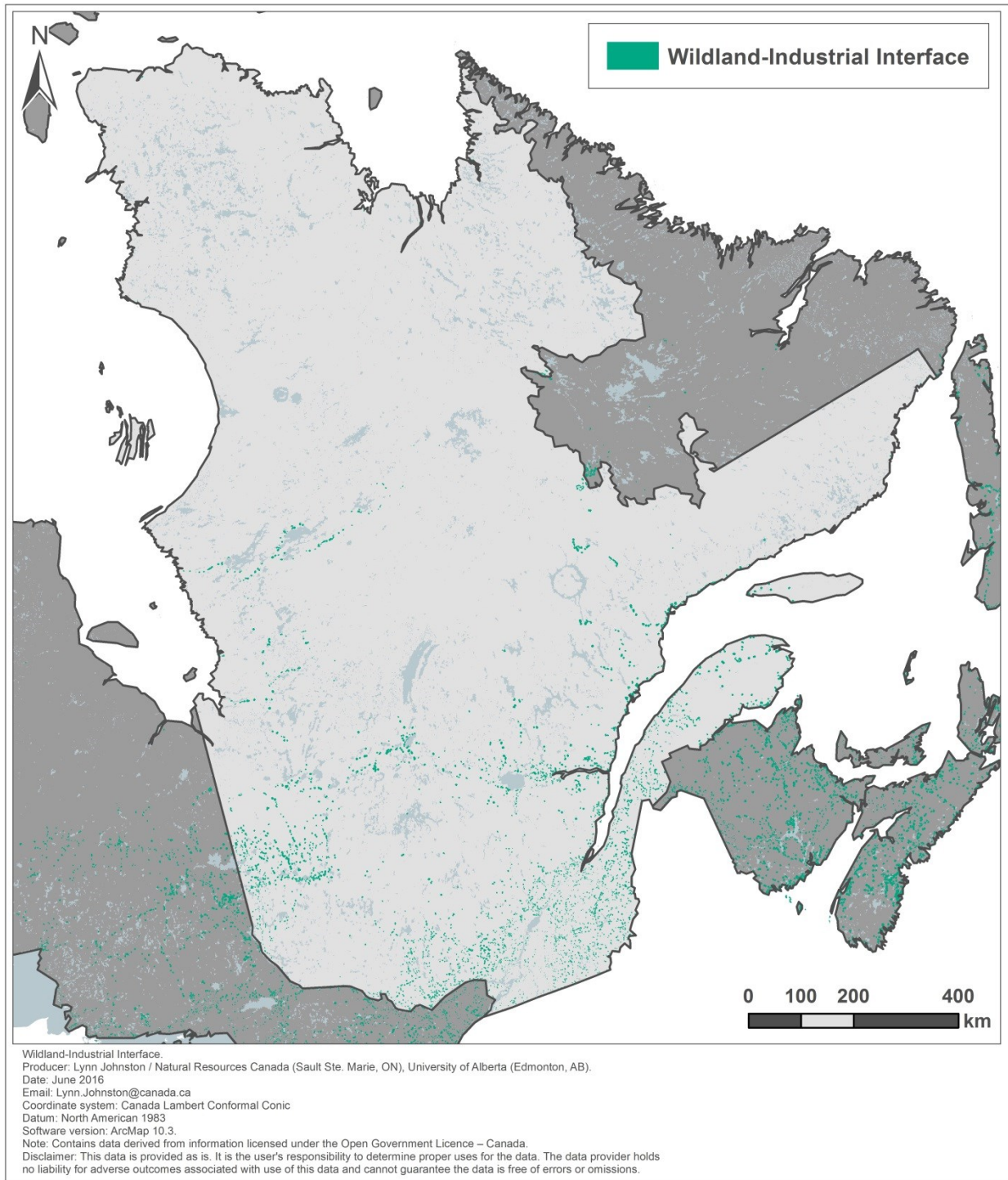
Figure A2-9. Infrastructure interface map for Saskatchewan.
Map of infrastructure interface for Saskatchewan. Inland hydrology is light blue, the area of interest is light grey, and the reminder of Canada is dark grey. There are 7.50 million ha of infrastructure interface in the province, which covers 13.06% of its land area, or 21.76% of its wildland fuel area.
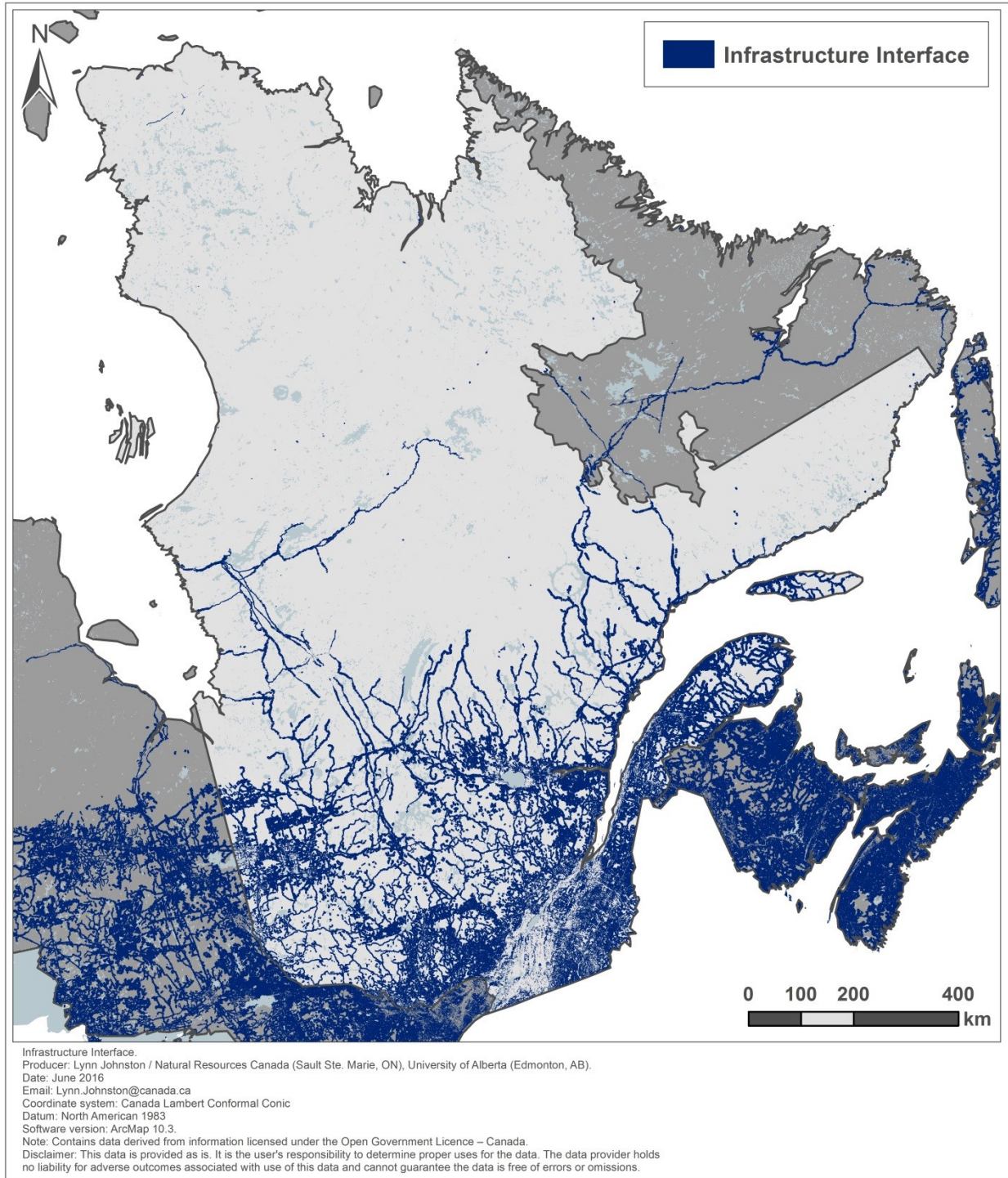
Figure A2-10. Wildland-urban interface map for Manitoba.
Map of wildland-urban interface (WUI) for Manitoba. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 2.28 million ha of WUI in the province, which covers 4.38% of its land area, or 5.04% of its wildland fuel area.

Figure A2-11. Wildland-industrial interface map for Manitoba.
Map of wildland-industrial interface (WII) for Manitoba. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 390 thousand ha of WII in the province, which covers 0.75% of its land area, or 0.86% of its wildland fuel area.

Figure A2-12. Infrastructure interface map for Manitoba.
Map of infrastructure interface for Manitoba. Inland hydrology is light blue, the area of interest is light grey, and the reminder of Canada is dark grey. There are 7.02 million ha of infrastructure interface in the province, which covers 13.46% of its land area, or 15.52% of its wildland fuel area.

Figure A2-13. Wildland-urban interface map for Ontario.
Map of wildland-urban interface (WUI) for Ontario. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 5.85 million ha of WUI in the province, which covers 6.65% of its land area, or 7.34% of its wildland fuel area.
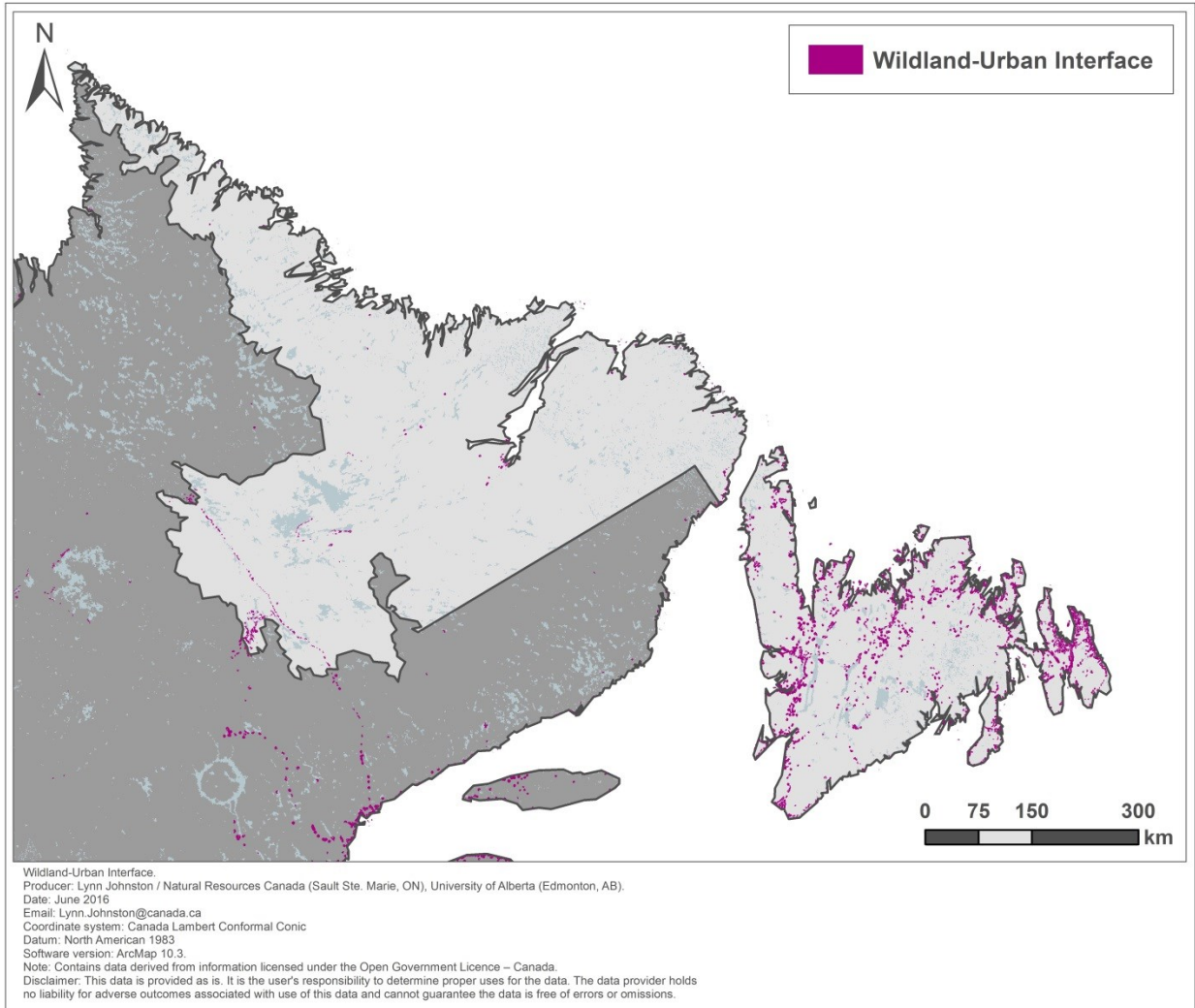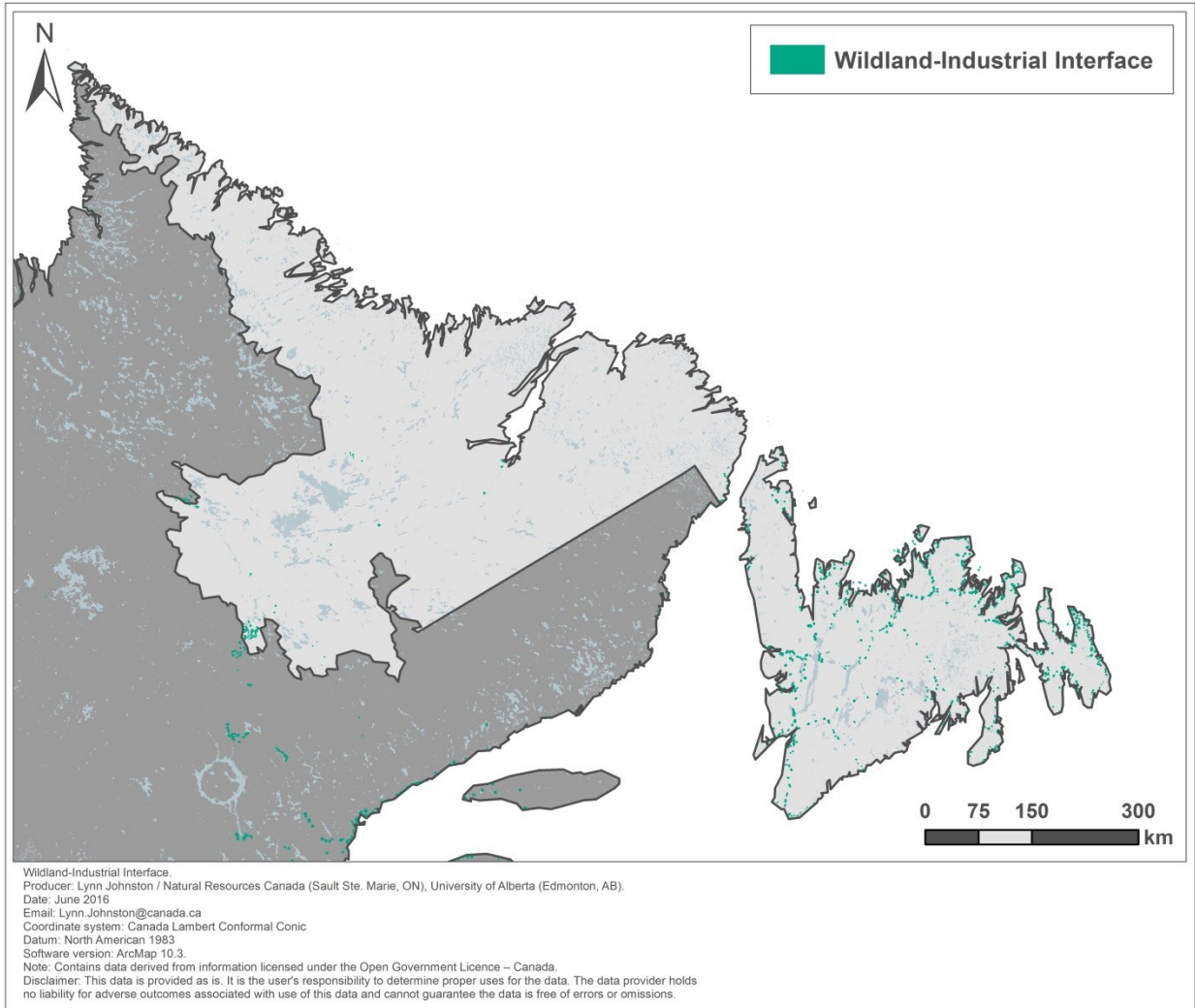
Figure A2-14. Wildland-industrial interface map for Ontario.
Map of wildland-industrial interface (WII) for Ontario. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 1.23 million ha of WII in the province, which covers 1.40% of its land area, or 1.55% of its wildland fuel area.

Figure A2-15. Infrastructure interface map for Ontario.
Map of infrastructure interface for British Columbia. Inland hydrology is light blue, the area of interest is light grey, and the reminder of Canada is dark grey. There are 21.57 million ha of infrastructure interface in the province, which covers 24.49% of its land area, or 27.06% of its wildland fuel area.
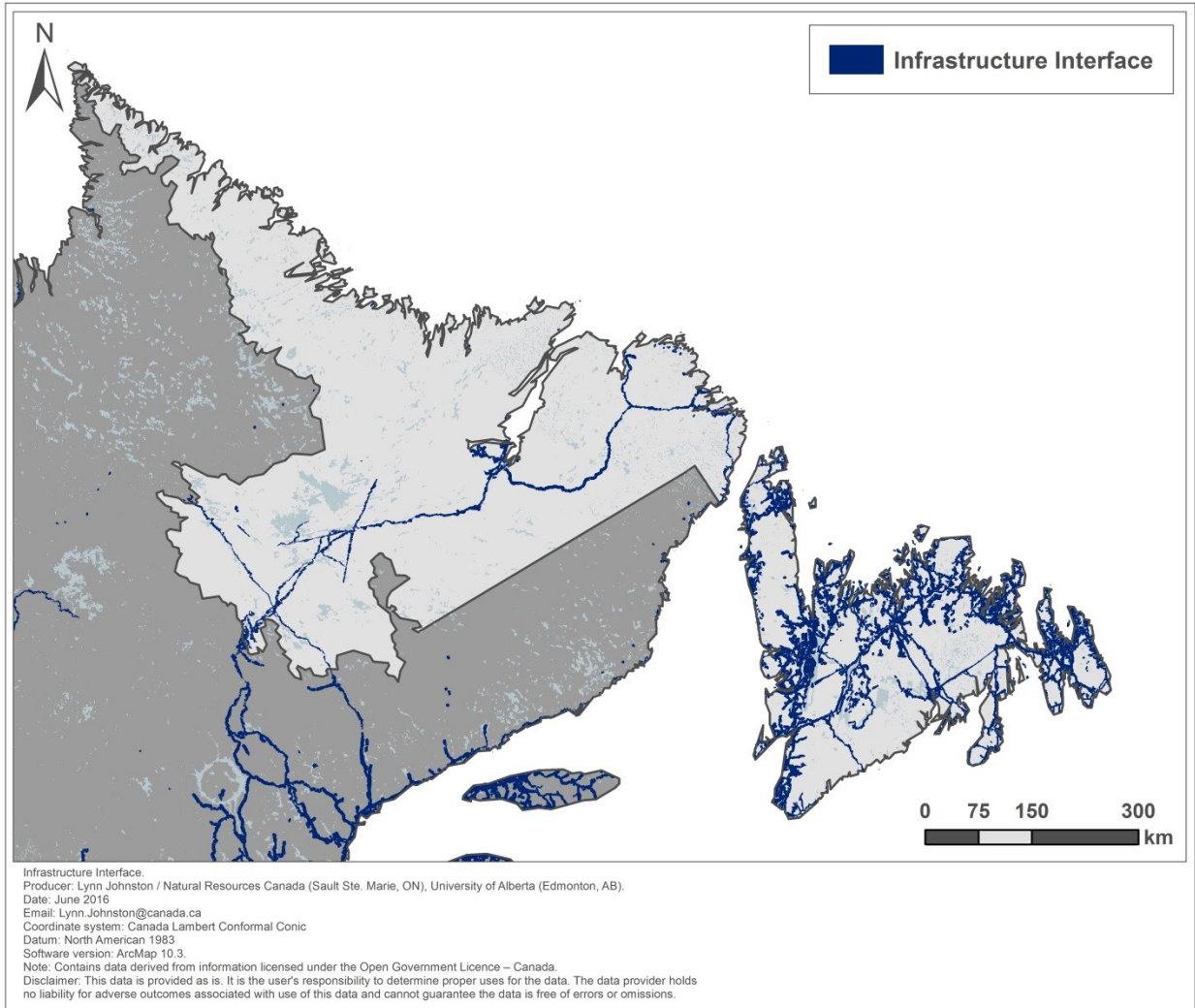
Figure A2-16. Wildland-urban interface map for Quebec.
Map of wildland-urban interface (WUI) for Quebec. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 6.98 million ha of WUI in the province, which covers 5.64% of its land area, or 7.02% of its wildland fuel area.
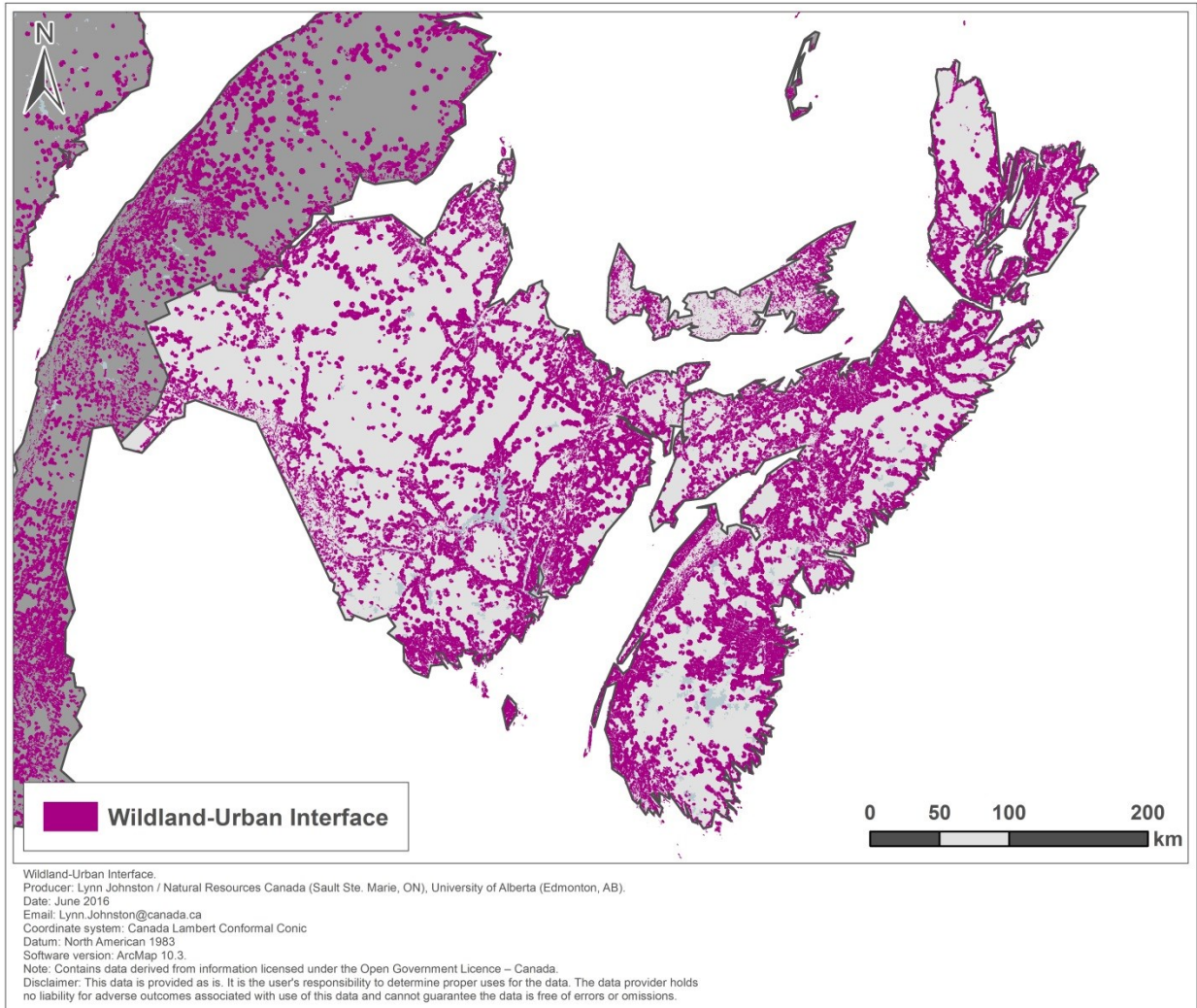
Figure A2-17. Wildland-industrial interface map for Quebec.
Map of wildland-industrial interface (WII) for Quebec. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 1.47 million ha of WII in the province, which covers 1.19% of its land area, or 1.48% of its wildland fuel area.

Figure A2-18. Infrastructure interface map for Quebec.
Map of infrastructure interface for Quebec. Inland hydrology is light blue, the area of interest is light grey, and the reminder of Canada is dark grey. There are 18.47 million ha of infrastructure interface in the province, which covers 14.91% of its land area, or 18.57% of its wildland fuel area.

Figure A2-19. Wildland-urban interface map for Newfoundland and Labrador.
Map of wildland-urban interface (WUI) for Newfoundland and Labrador. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 1.22 million ha of WUI in the province, which covers 3.57% of its land area, or 4.54% of its wildland fuel area.

Figure A2-20. Wildland-industrial interface map for Newfoundland and Labrador.
Map of wildland-industrial interface (WII) for Newfoundland and Labrador. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 500 thousand ha of WII in the province, which covers 1.47% of its land area, or 1.87% of its wildland fuel area.

Figure A2-21. Infrastructure interface map for Newfoundland and Labrador.
Map of infrastructure interface for Newfoundland and Labrador. Inland hydrology is light blue, the area of interest is light grey, and the reminder of Canada is dark grey. There are 3.72 million ha of infrastructure interface in the province, which covers 10.89% of its land area, or 13.84% of its wildland fuel area.
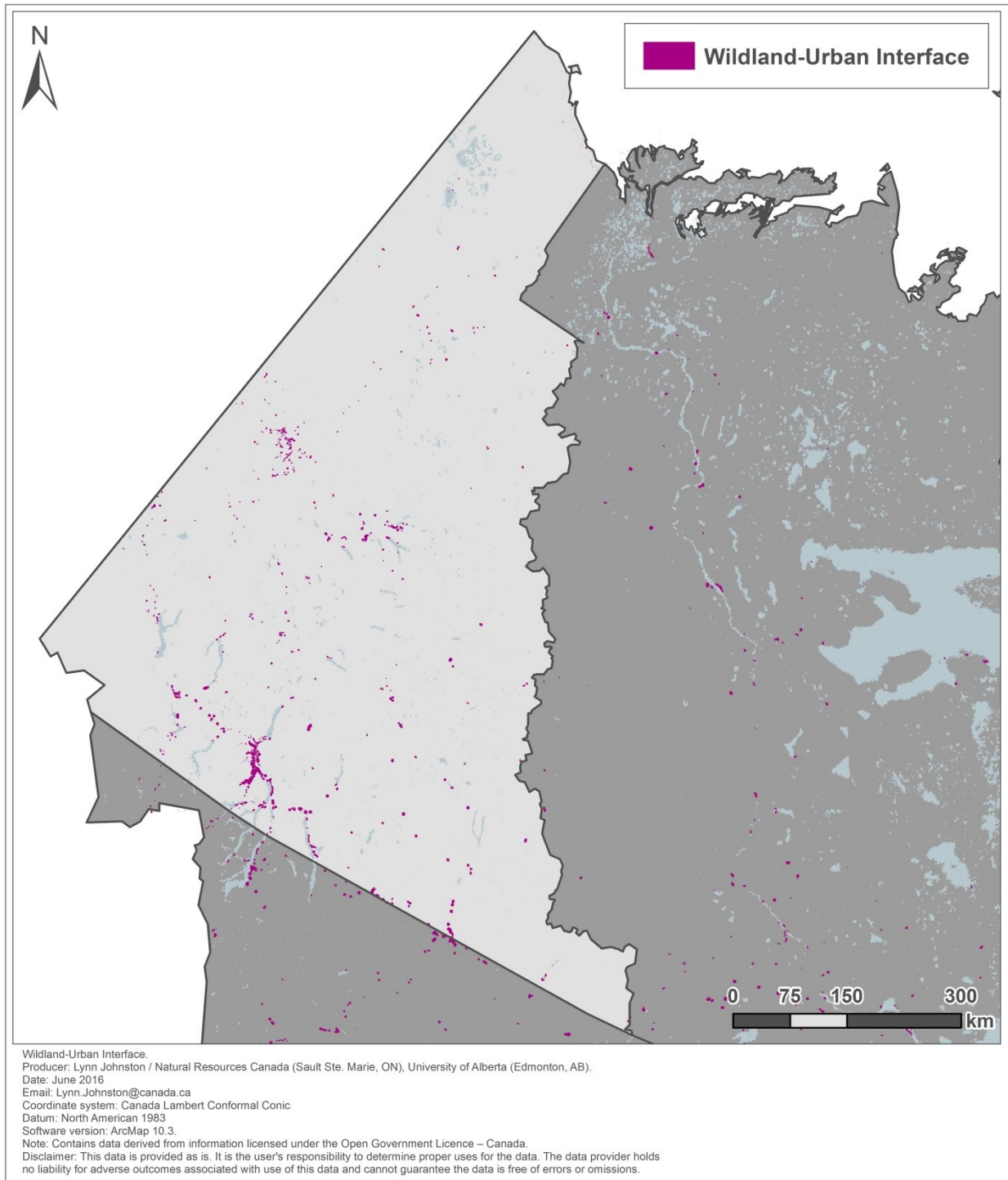
Figure A2-22. Wildland-urban interface map for New Brunswick, Prince Edward Island, and Nova Scotia.

Map of wildland-urban interface (WUI) for New Brunswick, Prince Edward Island, and Nova Scotia. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. For New Brunswick, there are 2.22 million ha of WUI in the province, which covers 30.62% of its land area, or 35.57% of its wildland fuel area. For Prince Edward Island, there are 180 thousand ha of WUI in the province, which covers 31.07% of its land area, or 75.23% of its wildland fuel area. For Nova Scotia, there are 2.43 million ha of WUI in the province, which covers 45.11% of its land area, or 53.00% of its wildland fuel area.
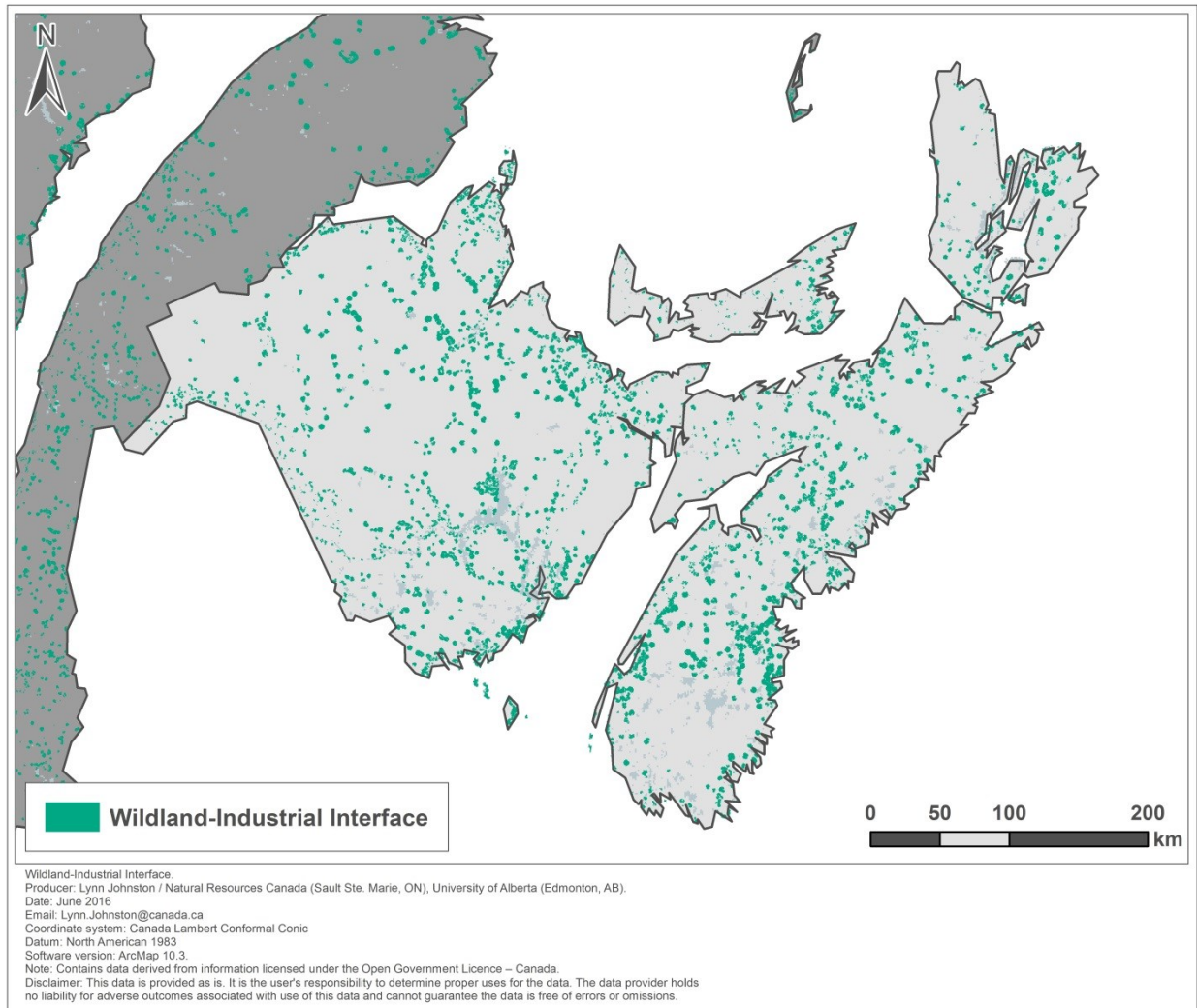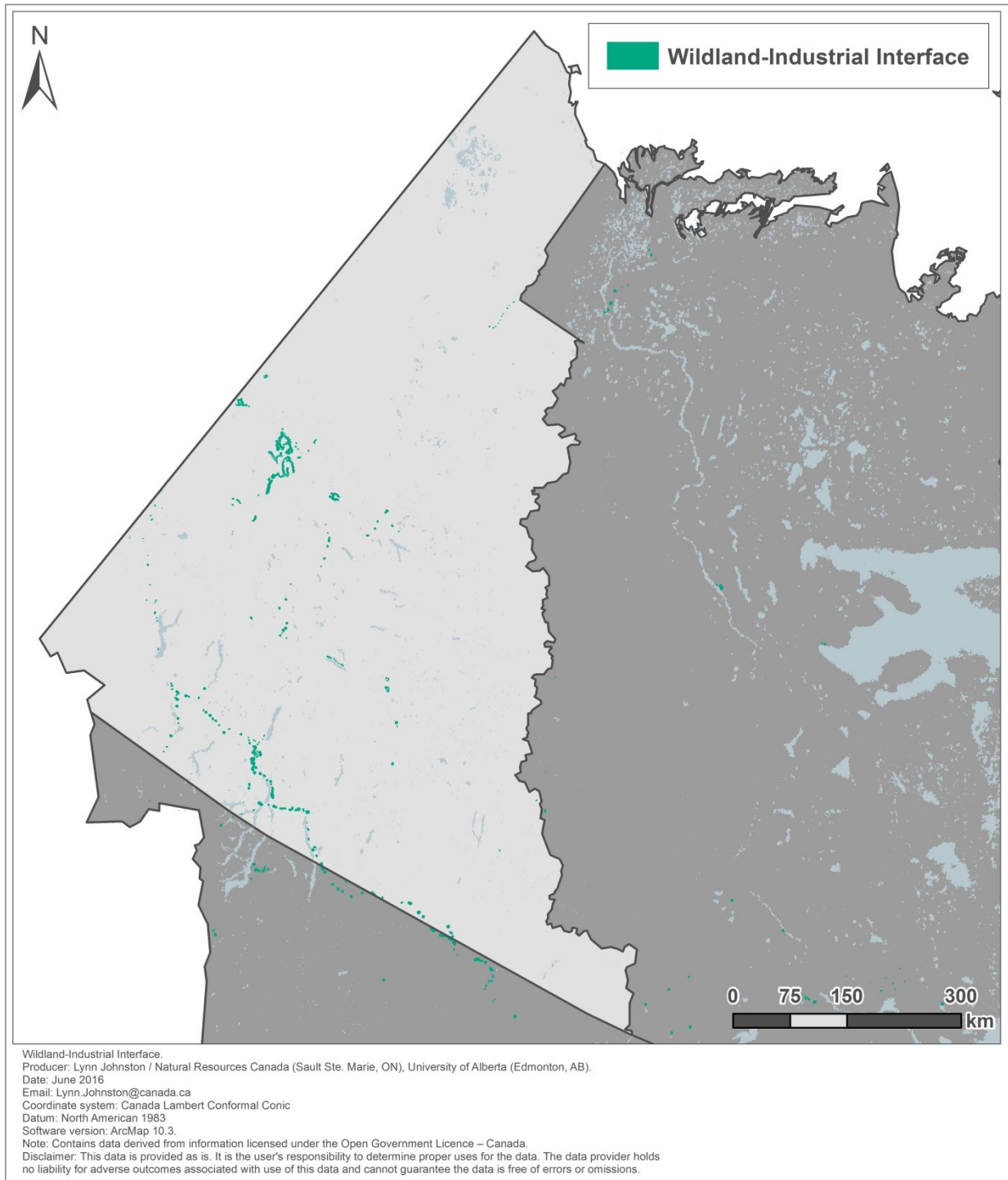
Figure A2-23. Wildland-industrial interface map for New Brunswick, Prince Edward Island, and Nova Scotia.

Map of wildland-industrial interface (WII) for New Brunswick, Prince Edward Island, and Nova Scotia. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. For New Brunswick, there are 580 thousand ha of WII in the province, which covers 7.92% of its land area, or 9.20% of its wildland fuel area. For Prince Edward Island, there are 30 thousand ha of WII in the province, which covers 5.14% of its land area, or 12.44% of its wildland fuel area. For Nova Scotia, there are 500 thousand ha of WII in the province, which covers 9.19% of its land area, or 10.79% of its wildland fuel area.
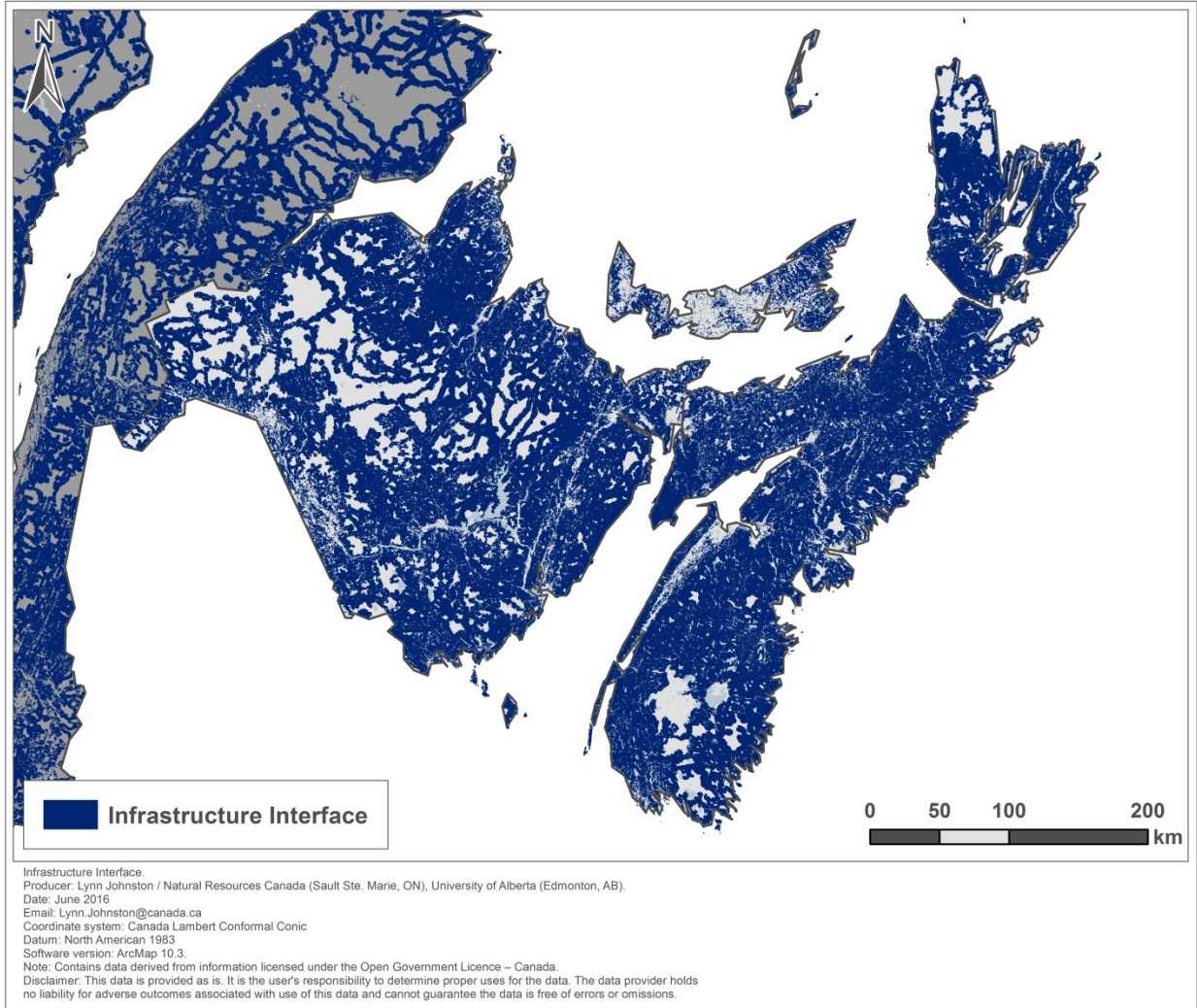
Figure A2-24. Infrastructure interface map for New Brunswick, Prince Edward Island, and Nova Scotia.

Map of infrastructure interface for New Brunswick, Prince Edward Island, and Nova Scotia. Inland hydrology is light blue, the area of interest is light grey, and the reminder of Canada is dark grey. For New Brunswick, there are 4.83 million ha of infrastructure interface in the province, which covers 66.51% of its land area, or 77.26% of its wildland fuel area. For Prince Edward Island, there are 220 thousand ha of infrastructure interface in the province, which covers 38.56% of its land area, or 93.37% of its wildland fuel area. For Nova Scotia, there are 4.15 million ha of infrastructure interface in the province, which covers 77.00% of its land area, or 90.47% of its wildland fuel area.
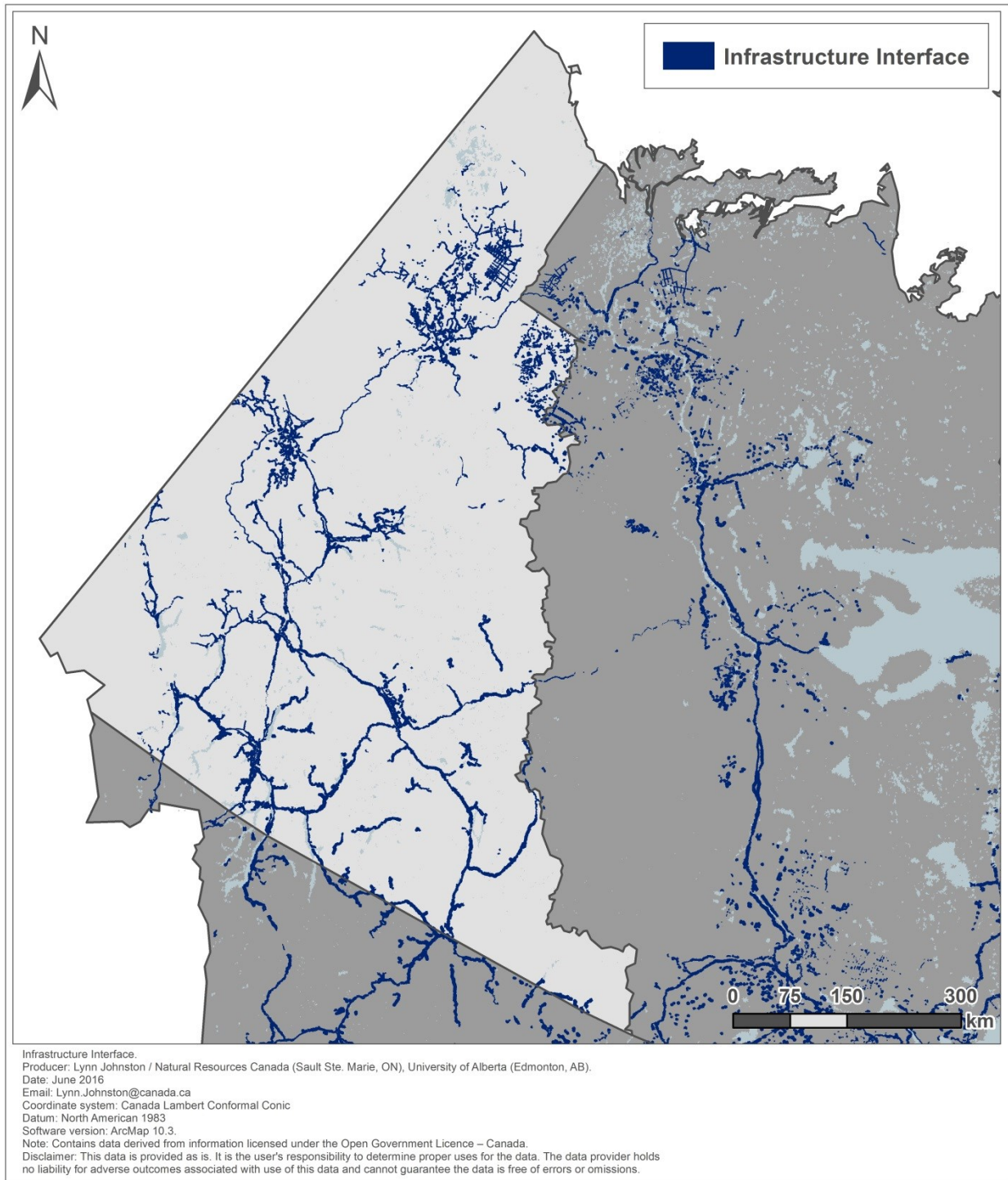
Figure A2-25. Wildland-urban interface map for Yukon.
Map of wildland-urban interface (WUI) for Yukon. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 290 thousand ha of WUI in the territory, which covers 0.67% of its land area, or 0.77% of its wildland fuel area.
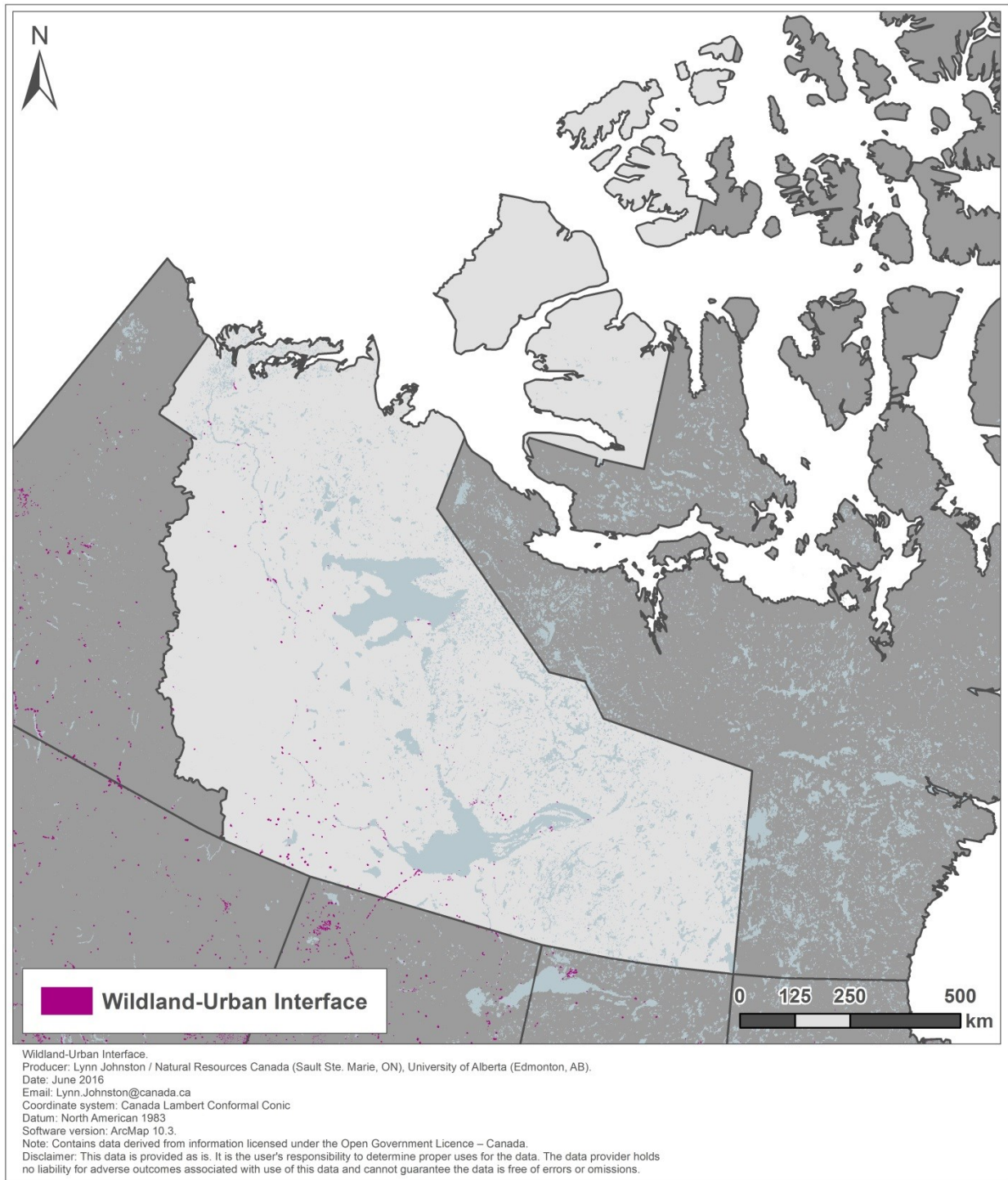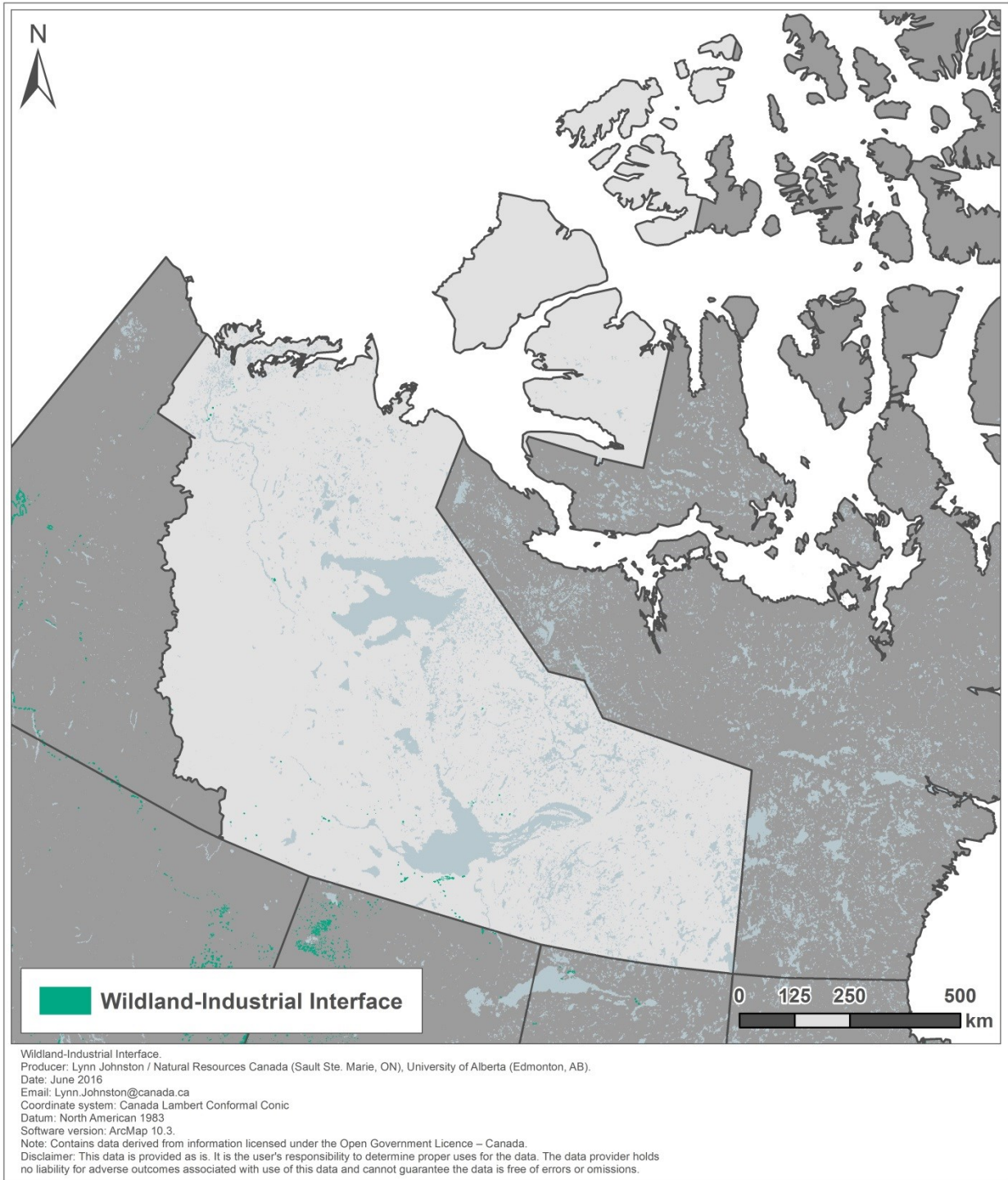
Figure A2-26. Wildland-industrial interface map for Yukon.
Map of wildland-industrial interface (WII) for Yukon. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 220 thousand ha of WII in the territory, which covers 0.51% of its land area, or 0.59% of its wildland fuel area.

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Figure A2-27. Infrastructure interface map for Yukon.
Map of infrastructure interface for Yukon. Inland hydrology is light blue, the area of interest is light grey, and the reminder of Canada is dark grey. There are 3.11 million ha of infrastructure interface in the territory, which covers 7.03% of its land area, or 8.18% of its wildland fuel area.
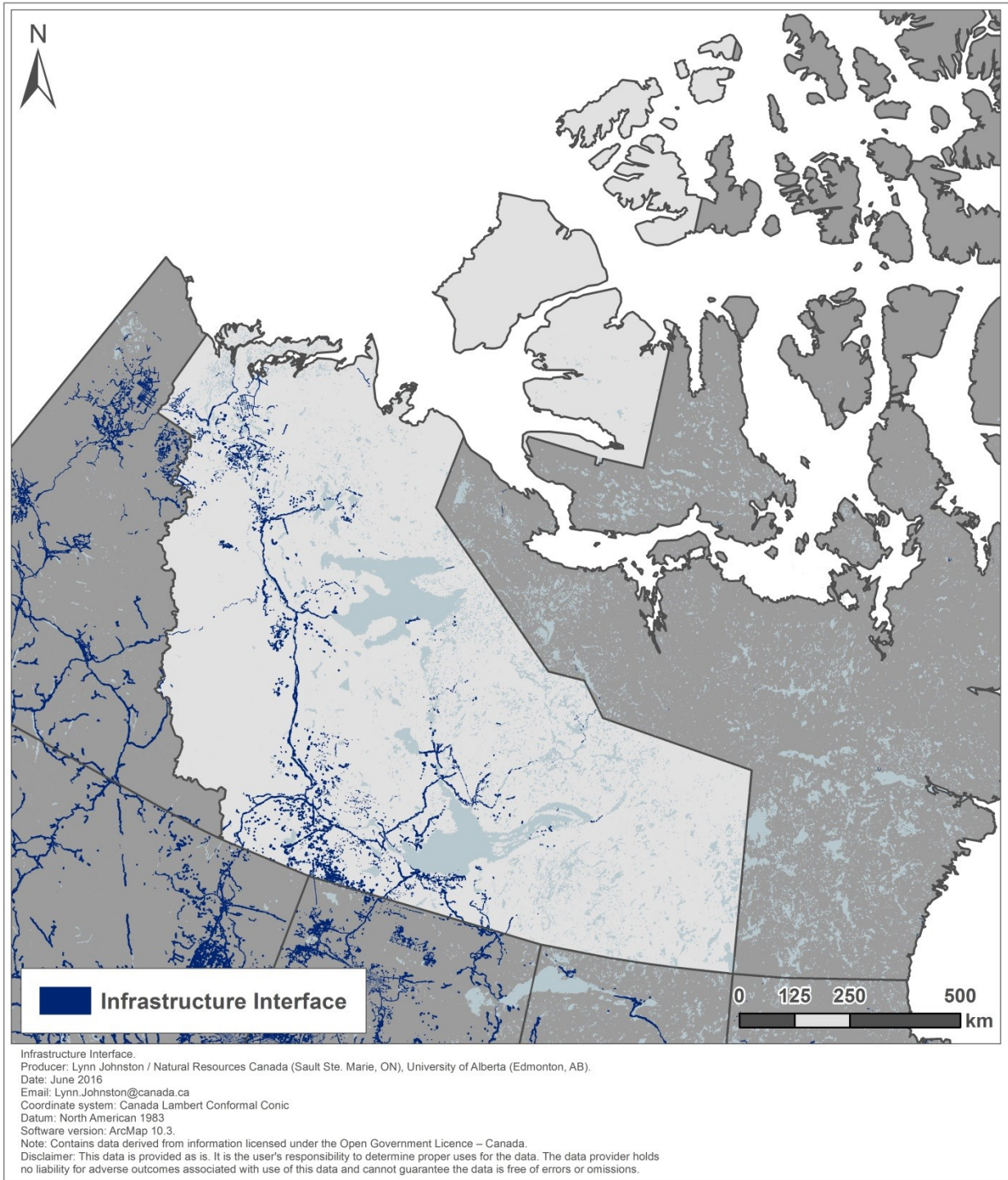
Figure A2-28. Wildland-urban interface map for Northwest Territories.
Map of wildland-urban interface (WUI) for Northwest Territories. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 200 thousand ha of WUI in the territory, which covers 0.19% of its land area, or 0.29% of its wildland fuel area.

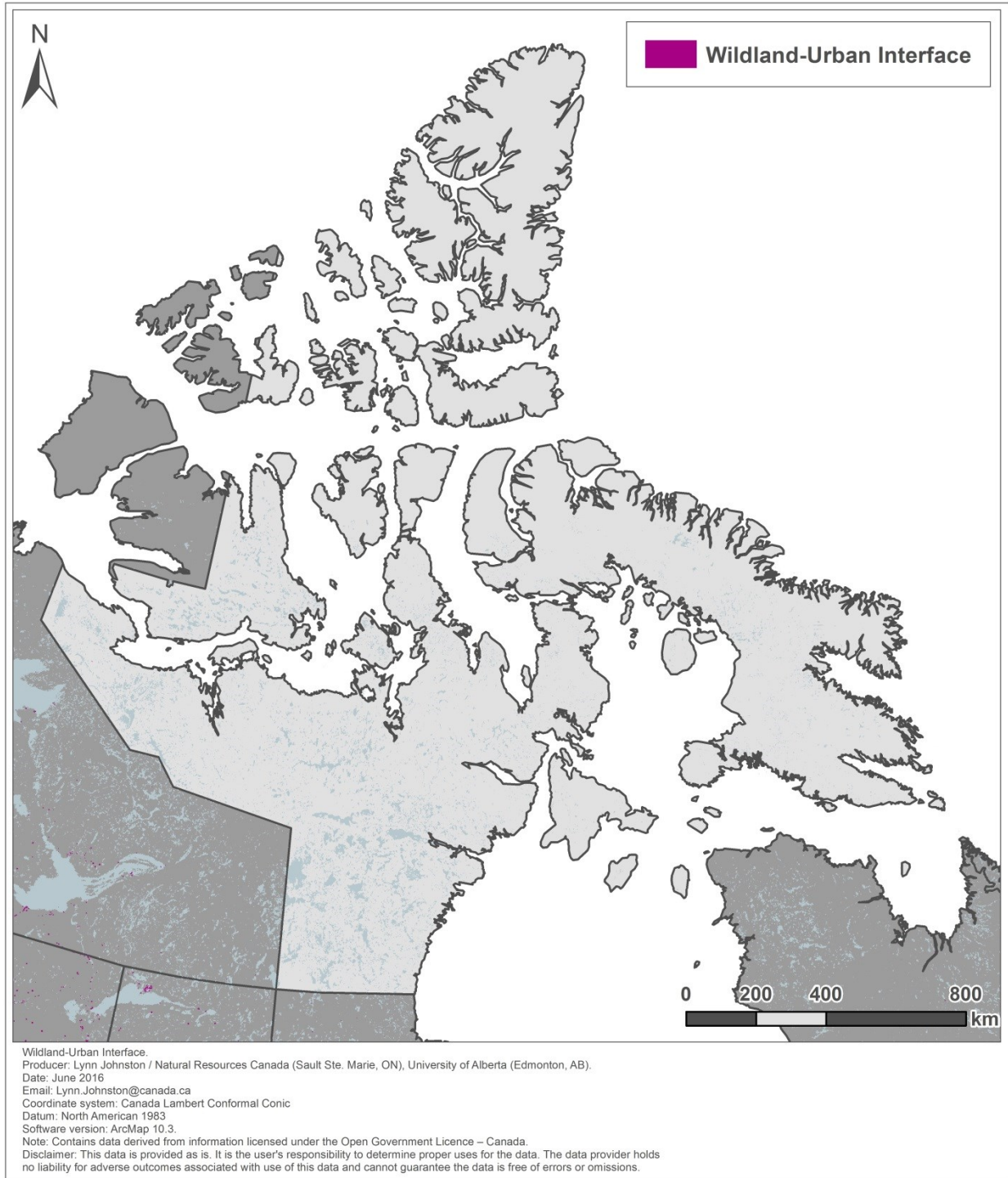**Figure A2-29. Wildland-industrial interface map for Northwest Territories.**
Map of wildland-industrial interface (WII) for Northwest Territories. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 70 thousand ha of WII in the territory, which covers 0.07% of its land area, or 0.10% of its wildland fuel area.

Figure A2-30. Infrastructure interface map for Northwest Territories.
Map of infrastructure interface for Northwest Territories. Inland hydrology is light blue, the area of interest is light grey, and the reminder of Canada is dark grey. There are 3.52 million ha of infrastructure interface in the territory, which covers 3.32% of its land area, or 5.01% of its wildland fuel area.
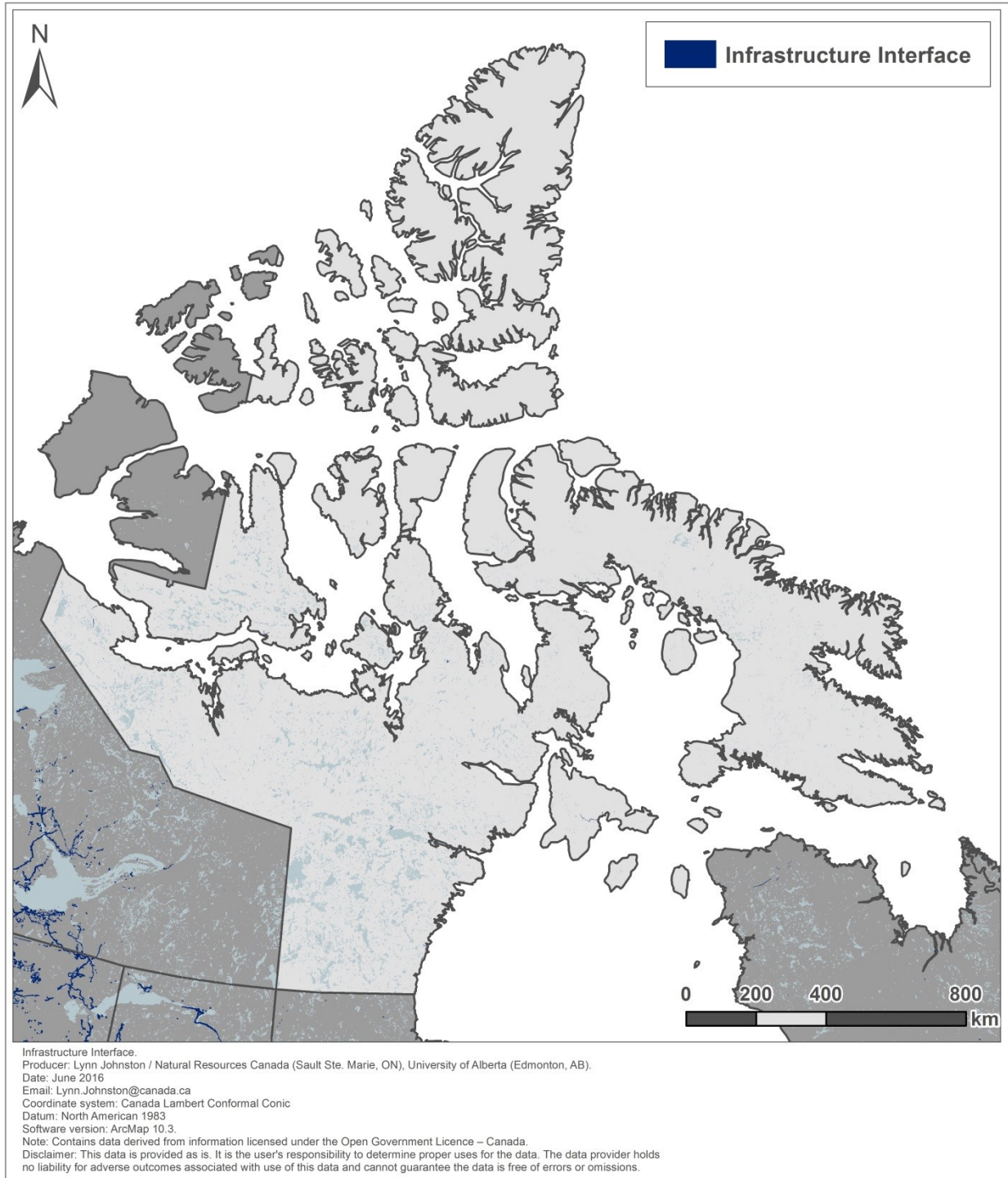
Figure A2-31. Wildland-urban interface map for Nunavut.
Map of wildland-urban interface (WUI) for Nunavut. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 5000 ha of WUI in the territory, which covers <0.01% of its land area, or 0.01% of its wildland fuel area.

Figure A2-32. Wildland-industrial interface map for Nunavut.
Map of wildland-industrial interface (WII) for Nunavut. Inland hydrology is light blue, the area of interest is light grey, and the remainder of Canada is dark grey. There are 1000 ha of WII in the territory, which covers <0.01% of its land area, or <0.01% of its wildland fuel area.

Figure A2-33. Infrastructure interface map for Nunavut.
Map of infrastructure interface for Nunavut. Inland hydrology is light blue, the area of interest is light grey, and the reminder of Canada is dark grey. There are 20 thousand ha of infrastructure interface in the territory, which covers 0.01% of its land area, or 0.06% of its wildland fuel area.