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Rating telecommunication towers by social importance and physical vulnerability to wildfire

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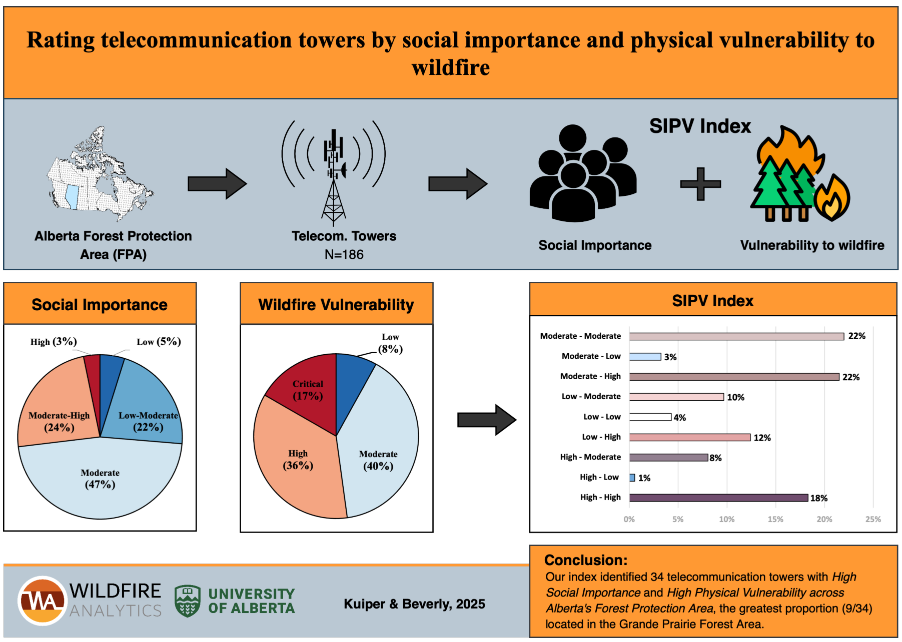
Abstract. Telecommunication infrastructure and the service it provides is vital for notifying threatened populations during wildfire events to ensure timely and safe evacuations. Much of the telecommunication infrastructure in the province of Alberta, Canada, is situated in fire-prone regions, with over 600 individual cell tower sites within the Forest Protection Area (FPA). Proactive measures such as fuel reduction treatments can reduce risk to communication infrastructure and support community resilience, but with limited resources available, there is a need to prioritize the most important and vulnerable towers for protective action. This study presents a structured framework for rating telecommunication infrastructure based on multiple factors of vulnerability. We developed an index that combines indicators of social importance (network redundancy, robustness, and intersection with developed lands and transportation infrastructure) and indicators of physical vulnerability to wildfire (fire exposure, directional vulnerability, slope, and suppression capability) to rate telecommunication towers in Alberta's FPA. In total, 34 telecommunication towers were identified as having both high social importance and high physical vulnerability to wildfire, with almost a quarter located in a single region, the Grande Prairie Forest Area. Potential applications of our Social Importance and Physical Vulnerability (SIPV) Index for informing protection and mitigation decisions are discussed.



Graphical Abstract.

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1 Introduction

The frequency, intensity, and socioeconomic impacts of wildfires are increasing globally due to climate change, significantly affecting vulnerable communities and critical infrastructure (Flannigan et al., 2009; Jain et al., 2024; Robinne et al., 2016). With its vast wildfire-prone landscapes, Alberta, Canada, exemplifies these challenges, experiencing regular severe fire seasons, most recently in 2023 and 2024. Wildfires can devastate the built environment, including destroying homes, businesses, and critical infrastructure such as electrical and telecommunication systems, often leaving residents displaced and disconnected during emergencies. Past wildfire-induced disruptions to telecommunications have been linked to damaged power lines that supply communication systems. Canada's northern territories, Yukon and Northwest Territories, faced widespread telecommunications outages in May 2024, illustrating the cascading risks posed by infrastructure failures during wildfires (CBC News, 2024; Cecco, 2024; Whitehorse Star, 2024). Direct burning of cellular towers and other telecommunication sites remains a growing concern that necessitates proactive identification of vulnerabilities and mitigation measures.

These vulnerabilities were evident in Hawaii, where the disastrous Maui 2024 fire burned over telecommunication infrastructure and left residents of the island without a means of communication (Kelly, 2023). Alberta's 2024 wildfire in Jasper National Park and the Jasper townsite exposed the challenges of ensuring communication in remote areas, where hikers, unable to receive alerts, required resource-intensive physical evacuations (Kaufmann, 2024; Shokeir, 2024). Carreras-Coch et al. (2022) document the pivotal role of communication technologies in disaster scenarios, where timely and accurate information dissemination can significantly influence emergency response effectiveness and community safety. Recent wildfire events have clearly demonstrated the indispensable role of telecommunications as a lifeline for public safety, disaster response, and wildfire management preparedness (Arab et al., 2021; Khalid et al., 2023).

Assessing the vulnerability of telecommunication infrastructure based solely on physical exposure to fire neglects the multi-dimensional nature of the vital services it provides. Telecommunications are not only physically vulnerable to direct damage from wildfires but are also integral to emergency response, public safety, and societal resilience. The conceptualization of vulnerability as a multi-dimensional construct is well-documented in disaster risk literature. Cutter et al. (1996) and Birkmann (2007) have emphasized the importance of integrating social, physical, and systemic vulnerabilities into comprehensive assessment frameworks. Frameworks like the wildfire vulnerability index developed by Papathoma-Köhle et al. (2022) emphasize physical vulnerability by quantifying the structural susceptibility of buildings to wildfire exposure. Oliveira et al. (2018) previously developed an alternative approach by incorporating geographic and operational factors to map wildfire vulnerability across Mediterranean Europe, providing practical tools for prioritizing risk management efforts. For critical infrastructure, Argyroudis et al. (2020) proposed a resilience assessment framework designed to evaluate infrastructure performance under multi-hazard scenarios, including wildfires. These frameworks collectively highlight the necessity of tailored methodologies that address the physical, functional, and operational vulnerabilities of critical infrastructure, such as telecommunication networks, to enhance disaster resilience.

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Despite the critical role of telecommunications, existing wildfire vulnerability assessments predominantly focus on residential structures or ecosystems (Beverly et al., 2010; Papathoma-Köhle et al., 2022), leaving telecommunication infrastructure underexplored. Alberta's Forest Protection Area (FPA), with 638 telecommunication sites and over 3,600 cellular transmitters (ISED Canada, 2023; Kuiper and Beverly, 2025), highlights the complexities of maintaining communication networks in wildfire-prone regions. These systems are vital for sparsely populated rural areas, Indigenous communities, and emergency response in remote locations (Asfaw et al., 2019; McMahon and Akçayır, 2022). Yet, there is no framework that evaluates both the societal importance and physical vulnerability of telecommunication infrastructure during wildfires, which presents as a critical gap in wildfire risk management.

Kuiper and Beverly (2025) identified 186 telecommunication towers in Alberta with extreme wildfire exposure (>45% exposure). That study focussed on the spatial intersection between wildfire exposure, tower sites, travel routes, and cell coverage gaps. Highly exposed road and trail networks without cell coverage were identified and individual towers were rated according to the number of viable pathways for potential fire encroachment following Beverly and Forbes (2023). In the present study, we focus on tower sites rather than travel routes, and develop a systematic, integrated framework for combining multiple physical vulnerability and social importance attributes within a single index. Tower exposure to wildfire and viable fire pathways assessed by Kuiper and Beverly (2025) were combined with additional indicators of physical vulnerability (i.e., suppression capability and slope) and social importance indicators to create a Social Importance and Physical Vulnerability (SIPV) Index. Our approach combines stepwise mapping methodologies (Oliveira et al., 2018), bivariate mapping techniques (Andersen and Sugg, 2019), and vulnerability indices (Andersen and Sugg, 2019; Cetin et al., 2023; Mandalapu et al., 2024; Mhawej et al., 2017; Papathoma-Köhle et al., 2022), with the aim of providing actionable insights to inform wildfire mitigation efforts by telecommunication providers and wildfire management agencies. We expect the findings presented here will contribute to strategic resource allocation, enhanced resilience planning, and improved decision-making, ensuring critical communication systems remain operational during wildfire emergencies.

2 Methods

Our methodological workflow is outlined in the following sections and visually illustrated in Fig. 1.

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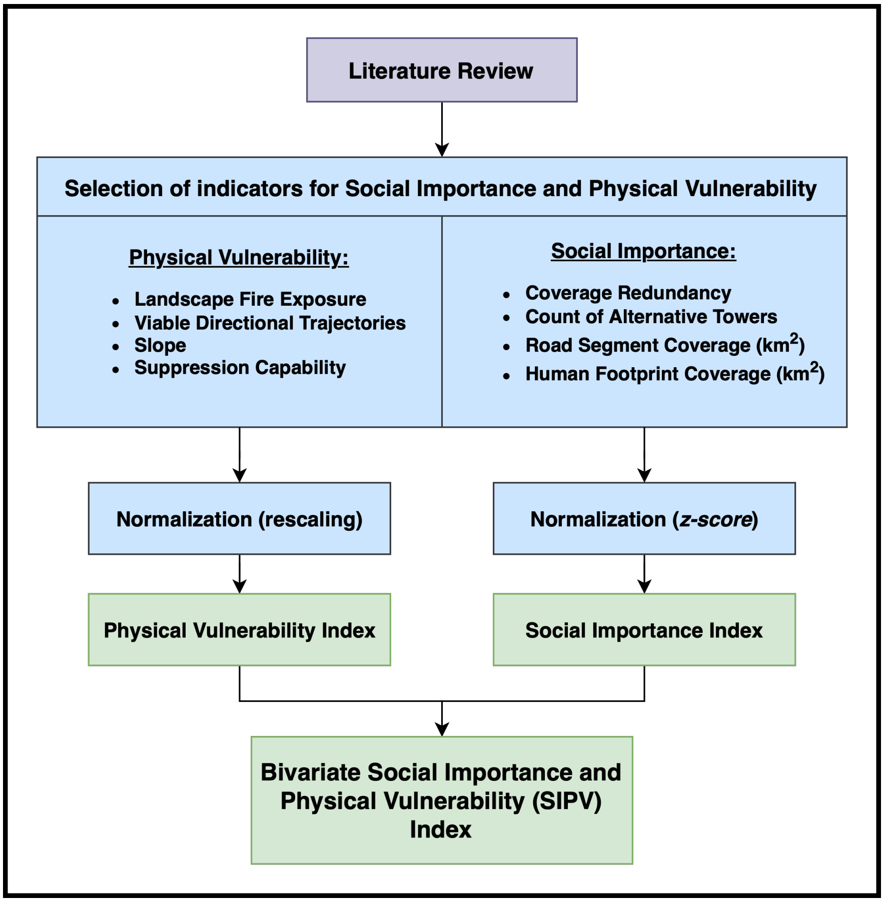

Figure 1: Methodological workflow illustrating the development process for the Social Importance & Physical Vulnerability Index (SIPV Index).

2.1 Study area

The study area is bounded by Alberta's Forest Protection Area (FPA), which has a land area of 390,000 km^2 and is divided into ten administrative units (i.e., Forest Areas, Fig. 2). Within the FPA, wildfire management is the responsibility of a provincial government agency, the Alberta Wildfire Management Branch. Alberta's landscape is classified into six ecological regions and twenty-one subregions, as defined by the Natural Regions Committee (2006), based on a combination of vegetation, soils, physiography, and landscape features. Seventeen subregions fall within the FPA, with the majority located in the Boreal Forest Natural Region.

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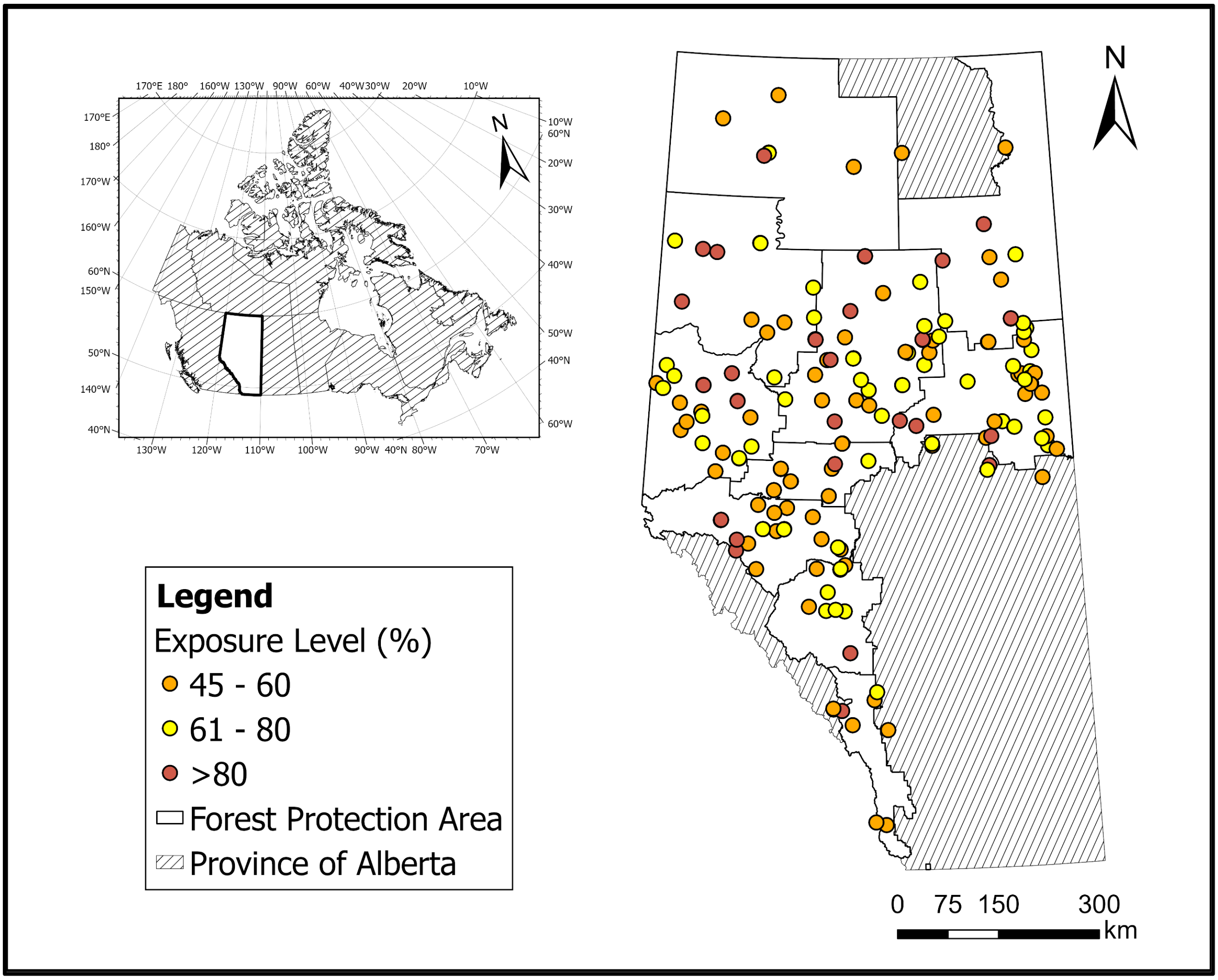

Figure 2: Telecommunications towers (n = 186) in Alberta's Forest Protection Area (FPA) with extreme wildfire exposure (>45%) identified by Kuiper and Beverly (2025)**. Colour ramp denotes exposure level.**

A national data set of radio-telecommunication spectrum licences was obtained from the Canadian Radio-television and Telecommunications Commission (CRTC) and used to geolocate telecommunication towers present in the FPA (ISED Canada, 2023). For the purposes of this study, we restricted our analysis exclusively to the telecommunication type of *cellular*, or those operating at ~800 MHz (megahertz). Additionally, our analysis was limited to telecommunication infrastructure previously identified as extremely exposed to wildfire by Kuiper and Beverly (2025). In total, 186 telecommunication towers were assessed. These towers have a relatively even distribution across the province with the exception of northernmost regions, where towers are comparatively sparse (Fig. 2).

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2.2 Data sources

Varied data sources indicative of either social importance (Table 1) or physical vulnerability (Table 1) were used to compute respective sub-indexes, which were then merged into a Social Importance and Physical Vulnerability (SIPV) Index.

Table 1: Societal importance and physical vulnerability indicators with associated descriptions and data sources

Variable	Description	Source
	Social Importance	
Coverage Overlap	Percent of a telecommunication towers coverage area that intersects with coverage areas of alternative towers	Computed from tower location data from the Canadian Radio-television and Telecommunications Commission (CRTC) (ISED Canada, 2023). Coverage areas estimated by Kuiper and Beverly (2025).
Nearby Towers	Count of alternative telecommunication infrastructure within a 20 km radius of the operating tower.	Computed using tower location data supplied by the CRTC (ISED Canada, 2023).
Road Coverage	Area (km^2) of road segments intersected by a tower's coverage area.	Computed from road network data Government of Alberta (2024) using segmentation methods and tower coverage areas estimated by Kuiper and Beverly (2025).
Human Footprint Coverage	Area (km^2) of the ABMI Human Footprint intersected by a tower's coverage area.	Computed from Alberta Biodiversity Monitoring Institute (2021). Tower coverage computed from CRTC location data and coverage areas estimated by Kuiper and Beverly (2025).
	Physical Vulnerability	
Fire Exposure	Relative rating of the potential for fire transmission to a location. Calculated as the percent (%) of hazardous cover types within a 500 m circular neighbourhood where hazardous cover is defined by the presence of conifer fuel types.	Computed by Kuiper and Beverly (2025) following Beverly et al. 2021
Directional Vulnerability	Count of viable directional pathways of continuous high fire exposure (> 60%).	Computed by Kuiper and Beverly (2025) Following Beverly and Forbes (2023).

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Suppression Capability	Calculated as the nearest average distance to either an Air Tanker base or lake of sufficient size to accommodate Skimmer aircraft.	Alberta Wildfire (2024).
Slope	Calculated as the relative measure of terrain steepness, calculated from a provincial Digital Elevation Model (DEM).	[NO_PRINTED_FORM] (Alberta provincial digital elevation model, 2025).

2.3 Social importance

Previous assessments of telecommunications infrastructure vulnerability to wildfire generally omit social importance. Aspects of socioeconomic vulnerability have been considered in prior assessments of wildfire vulnerability (Andersen and Sugg, 2019; Papathoma-Köhle et al., 2022). Kuiper and Beverly (2025), identified exposed travel routes (i.e., trails and roads) that lacked telecommunications coverage. In the present study, we aimed to rate the social importance of an individual tower based on indicators of network redundancy, robustness, and intersection with urban/developed lands and vital transportation infrastructure (Eiselt and Marianov, 2012; Zimmerman, 2001). The social importance index of telecommunication infrastructure was computed from four indicators detailed below: coverage area intersection, alternative infrastructure, coverage of the human footprint (i.e., the ABMI human footprint), and coverage of roads.

2.3.1 Coverage area redundancy

Coverage areas for all tower in the assessment area reported by Kuiper and Beverly (2025) were used to assess areas of overlap (i.e., redundancy) in tower coverage. Coverage area intersections were calculated for each highly exposed tower included in our analysis (n = 186). Although multiple transmitters are present on a single tower, towers were treated as a single entity and coverage areas were merged into one. The level of redundancy associated with a given tower was computed as the percentage of the tower's total coverage area (0-100%) that intersects the coverage areas of other towers. A python script was developed to perform the intersection operations by isolating each tower's coverage area and intersecting coverage areas of all other infrastructure. High levels of redundancy associated with a given tower means that alternate coverage is available in the event of a wildfire disruption to that tower.

2.3.2 Tower redundancy

Telecommunications infrastructure may have most of its coverage area intersected by the coverage supplied by other towers, but the number of alternative towers is relevant. In the event of a wildfire disruption to a given tower, alternative towers tasked with supplying substitute coverage may lack bandwidth capacity to do so. The total count of nearby infrastructure, or tower redundancy, was calculated for each individual tower within its operating distance (i.e., 40 km) and assigned as the variable *nearby towers*.

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2.3.3 Human footprint coverage

Human presence was delineated by the Alberta Biodiversity Monitoring Institute (ABMI) human footprint geospatial layer, which provides a digital representation of anthropogenic disturbances across the provincial landbase (Alberta Biodiversity Monitoring Institute, 2021). Only data layers indicating permanent or semi-permanent human occupation were retained for analysis. Features such as oil and gas wellsites, seismic lines, pipelines, roads, and other features that indicate anthropogenic disturbance, but not permanent human occupation were removed. The following feature types were included: RURAL-/URBAN-/COUNTRY-RESIDENCES, URBAN-INDUSTRIAL, CAMP-INDUSTRIAL, TRANSFER_STATION, FACILITY, RESIDENTIAL CLEARING, MILL, RECREATION, CAMPGROUND, GREENSPACE, AND GOLFCOURSE. A python script was utilized to iterate through tower points to calculate the area (km^2) of intersection between each telecommunication tower's coverage area and the human footprint.

2.3.4 Transportation infrastructure

Telecommunications coverage of the road network within the FPA was previously investigated by Kuiper and Beverly (2025) where a significant proportion of road segments were identified as vulnerable to fire exposure and lacking telecommunications coverage. We used a similar approach, segmenting roads every 500 m and buffering them outwards 100 m. To quantify the importance of telecommunication infrastructure with respect to roads, coverage areas were intersected with road segments within the study area. This resulted in each tower being assigned a value in square kilometres representing the area of road segments covered by each towers communication viewshed.

2.3.5 Social vulnerability index

Following the methods of Andersen and Sugg (2019), social importance indicators were normalized using z-score standardization and subsequently summed based on the directionality of the relationship between the variable and level of vulnerability (Table 2) for each tower.

Table 2. Index variables and relationship direction (+, –) by rating (high, low) and sub-index (physical vulnerability, social importance).

Index Rating	Index Variable and relationship direction (+, –)	
	Physical Vulnerability	Social Importance
High	+ Fire Exposure + Directional Vulnerability + Suppression Capability + Slope	– Coverage Overlap – Nearby Towers + Road Coverage + Human Footprint Coverage

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Low	– Fire Exposure – Directional Vulnerability – Suppression Capability – Slope	+ Coverage Overlap + Nearby Towers – Road Coverage – Human Footprint Coverage

2.4 Physical vulnerability

Telecommunication infrastructure is susceptible to wildfire damage due to the structural materials and site characteristics. A typical tower site consists of an area cleared of vegetation, with a recommended diameter of 20 to 50 metres (Butler et al., 2014) (Figure 3). This cleared area hosts sensitive infrastructure such as the steel lattice tower structure, electronic equipment, and power sources like a backup generator or communications hut to physically connect the tower to the power grid (Anderson et al., 2020). All this infrastructure and equipment is susceptible to damage from wildfire. Additionally, galvanized steel towers, commonly used for telecommunications infrastructure, can degrade at an accelerated rate due to the combined damaging effects of high heat (i.e., from a wildfire) and corrosion, compromising structural integrity (Zamanzadeh et al., 2024).

Figure 3: Image of vulnerable telecommunication tower site located near Red Earth, Alberta, Canada.

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Wildfire in Alberta's boreal forests can attain extreme fire intensities that hinder suppression capabilities due to a fire regime characterized by high crown fire potential, leading to rapid fire spread and large flame lengths (Beverly et al., 2020). Fuel complexes that consist of conifer-dominated forests with a continuous and connected arrangement of fine canopy fuels (i.e., needles and small branchwood) are conducive to high intensity crown fires and uninterrupted fire spread. Fuel continuity plays a crucial role in determining fire behaviour and the likelihood of a fire reaching a point of interest (Beverly et al., 2009; Phelps and Beverly, 2022). Wildfire does not spread in a uniform pattern across the landscape, rather it follows pathways determined by the fuels present, topographical features, and weather conditions (Holsinger et al., 2016). We rated a given tower's physical vulnerability to wildfire by combining the fuel-based assessment reported by Kuiper and Beverly (2025) with two additional indicators: slope and suppression capability.

2.4.1 Fire exposure and directional vulnerability

The proximity of a telecommunications site to surrounding hazardous fuels as well as the amount and arrangement of the hazardous fuel will determine the potential for wildfire damage. Previous research has shown that models incorporating complex factors of that interaction such as weather and ignition sources often perform poorly (Beverly and McLoughlin, 2019). Simpler models based solely on proximity to hazardous fuels align better with real wildfires (Beverly et al., 2021) and can be used to assess directional vulnerability of a point location to fire encroachment (Beverly and Forbes, 2023), providing a robust approach for evaluating telecommunication sites.

Fire exposure and directional vulnerability are two established indicators of physical vulnerability to wildfire (Beverly et al., 2021; Beverly and Forbes, 2023). Kuiper and Beverly (2025) identified 186 towers within the FPA of Alberta as having high wildfire exposure, quantified as the extent to which the tower is surrounded by hazardous fuel capable of transmitting fire to its location. Exposure is computed for a 500 m circular neighbourhood around a point of interest as the percent area occupied by hazardous fuel.

Kuiper and Beverly (2025) further assessed each high-exposure tower according to its directional vulnerability, which characterizes the broader pattern of exposure within a 15 km circular neighbourhood. Viable fire pathways are identified by the extent to which a given hypothetical fire trajectory intersects areas of high exposure, where an 80% intersection is used as threshold for viability. Pathways are assessed for 360 possible 1° directional trajectories and three distance segments (0-5 km, 5-10 km, and 10-15 km) extending outwards from the tower. Counts of viable trajectories provide a rating of directional vulnerability.

2.4.2 Slope

Terrain slope is a key physical factor influencing fire behaviour and has widely been used as a metric in wildfire vulnerability assessments (Papathoma-Köhle et al., 2022; Politi et al., 2024). The relationship between slope, fire intensity, and rate of spread (ROS) is well established in the wildfire literature (Butler et al., 2007; Cetin et al., 2023; Papathoma-Köhle et al., 2022; Sullivan, 2017). As slope increases, so does the rate of fire spread due to the preheating of fuels upslope and conversely with

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a downslope where fire spread rate follows a parabolic decremental pattern (Cetin et al., 2023; Wagner, 1988). This effect leads to significantly more intense fire behaviour, more rapid fuel consumption, and generally more unpredictable fire behaviour. Landscape fire exposure assessments do not explicitly account for slope because the primary consideration is not how fast a fire moves, but whether it can reach the location (Beverly et al., 2021).

Telecommunication infrastructure has a unique association with slope, due to the tendency to locate towers in areas of higher elevation that maximize signal transmission, provide a greater line of sight, and expand operational range (Al-Shehri et al., 2019). This preferential placement upslope increases tower vulnerability to rapid fire encroachment from lower elevations, which are more difficult to suppress. In such cases, slope may contribute to overall vulnerability, not because it influences landscape-scale fire exposure, but because it impacts the severity and intensity of fire behaviour as it reaches a telecommunications site. Therefore, we opted to incorporate slope to assess increased vulnerability to fire damage due to the increased fire behaviour associated with upslope spread.

To quantify slope in the terrain features around telecommunication infrastructure, we utilized a 25 m x 25 m Digital Elevation Model (DEM) raster layer acquired from the Government of Alberta (Alberta provincial digital elevation model, 2025). Using ArcGIS Pro (ESRI, 2024), we calculated the percent elevation change between raster cells to determine slope across the study area. Each telecommunication tower was assigned a value for slope corresponding to its geographical location, allowing us to assess how the surrounding topography may contribute to the vulnerability of a tower from an encroaching wildfire.

2.4.3 Suppression capability

When wildfire threatens critical infrastructure like telecommunications infrastructure, fire management agencies prioritize suppression resources to protect these assets. In Alberta, aerial firefighting is a key resource used in wildfire suppression operations with airtankers typically initiating fire suppression prior to arrival of ground crews, and sometimes exclusively when intensities exceed suppression capabilities of ground crews (Alberta Wildfire, 2025). Alberta maintains a fleet of airtankers that utilize either water collected in-flight from natural water bodies (i.e., skimmers) or retardant loaded from tanks when the aircraft is stationary at a base. Skimmers rely on relatively large bodies of water (i.e., lakes) to replenish their tanks, and retardant airtankers require airstrips equipped with fire retardant loading capabilities. In Alberta, both types of airtankers are staged at designated bases placed strategically across the province; however, skimmers do not need to return to the base in between drops on a fire, allowing for more frequent drops.

The proximity of telecommunication infrastructure to these key firefighting resources can influence the effectiveness of suppression efforts and the likelihood of successfully containing active fire threats before damage to infrastructure occurs. To quantify the potential for aerial fire suppression efforts to suppress wildfires threatening telecommunication infrastructure we measured the distance from each tower to either an active airtanker base, or water source large enough to support amphibious airtanker skimming operations. This analysis operates under the assumption that fires of sufficient size and intensity to jeopardize telecommunication assets would require aerial suppression. Distance to fire suppression resources have been used previously as an indicator of wildfire vulnerability (Mandalapu et al., 2024; Papathoma-Köhle et al., 2022). Prior studies have

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also utilized this metric in hazard or risk assessments for other types of infrastructure and natural disasters (Rashidi et al., 2018; Sutanto et al., 2024).

2.4.4 Physical vulnerability index

Exposure, viable pathways, slope and suppression capability were combined to compute a physical vulnerability index. Analytical Hierarchy Processes (AHP), Multi-Criteria Decision Making (MCDM), or equal weighting has been used in prior studies to classify multiple variable indices (Andersen and Sugg, 2019; Papathoma-Köhle et al., 2022). We opted for an equal weighting technique for variable classification, which may not fully represent the complex interactions involved in physical vulnerability to wildfire but provides a solid foundation that can be modified and tailored to specific needs and situations (Papathoma-Köhle et al., 2022). Following Andersen and Sugg (2019) and Papathoma-Köhle et al. (2022), physical indicators were classified into five bins with equal intervals (Table 3). Based on the relationship between physical vulnerability indicators and wildfire vulnerability (Table 2), the directionality influenced how variables were summed and averaged to create the mean physical vulnerability rating, calculated using Eq. (1):

$$PV(\bar{x}) = \frac{x_{exposure} + x_{dirVuln} + x_{slope} + x_{supp}}{n}, \qquad (1)$$

Where $x_{exposure}$ is the reclassified fire exposure rating, $x_{dirVuln}$ is the reclassified count of vulnerable directional pathways, x_{slope} is the reclassified slope rating, x_{supp} is the reclassified suppression capability rating, and n is the total count of variables. Ratings were subsequently assigned to each tower, with positively related indicators increasing vulnerability scores.

2.4 Intersection of social importance and physical vulnerability

Wildfire vulnerability assessments or indices have primarily focused on single-home structures, factoring in building materials, surrounding landscape, as well as factors impacting evacuation efficiency and fire suppression capability (i.e., distance to road, distance to fire station) (Andersen and Sugg, 2019; Mandalapu et al., 2024; Mhawej et al., 2017; Papathoma-Köhle et al., 2022; Penman et al., 2014). Additional indices have investigated the intersection of socioeconomic factors and physical vulnerability to wildfire (Andersen and Sugg, 2019; Wigtil et al., 2016); however, to our knowledge, no vulnerability index has been developed specifically for infrastructure or vital services such as the telecommunication network. The intention of this study is to provide a robust, customizable framework that identifies the extent of physically vulnerable and socially important telecommunication infrastructure exposed to potential wildfire. Following the methods of Andersen and Sugg (2019), Emrich and Cutter (2011), and Wigtil et al. (2016), a bivariate mapping technique was used to produce the intersection of social importance and physical vulnerability. To reduce the number of classifications from five to three for the social importance index, the two highest classifications (moderate-high and high) were combined to make the high classification, and the two lowest classifications (low and low-moderate) were combined to produce the low classification. Additionally, to reduce the number of classifications from four to three for the physical vulnerability index, the two highest classifications (high and critical) were combined to make the high classification.

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3 Results

Social importance scores were mapped following the procedures developed by Cutter et al. (2003) and implemented by Andersen and Sugg (2019) to classify scores into five bins based on standard deviations from the mean ranging from < – 1.5 to > 1.5 (Fig. 4; Table 3). Classes were identified as low, low-moderate, moderate, moderate-high, and high (Andersen and Sugg, 2019; Cutter et al., 2003). Of the 186 telecommunication towers assessed, 9 (4.84%) were classified as low, 40 (21.5%) as low-moderate, 87 (46.8%) as moderate, 44 (23.7%) as moderate-high, and 6 (3.23%) as high (Table 3). The Grande Prairie Forest Area contains 5 of 6 towers classified as high, with the remaining tower located in the adjacent High Level Forest Area (Table 3). The Peace River Forest Area contains 10 of 44 (22%) towers in the moderate-high social importance class (Table 3).

Table 4. Tower frequency by Social Importance and Physical Vulnerability classifications, proportion of towers within each class, and the Forest Area of holding the largest proportion of towers within each classification.

Class	Count	Most Common Forest Area (Count)
Social Importance		
Low	9	Calgary (5; 55.5%)
Low – Moderate	40	Lac La Biche (24; 60%)
Moderate	87	Slave Lake (26; 30%)
Moderate – High	44	Peace River (10; 22.7%)
High	6	Grande Prairie (5; 83%)
Physical Vulnerability		
Low	15	Lac La Biche (8; 53%)
Moderate	74	Lac La Biche (22; 29.7%)
High	66	Fort McMurray (11; 16.7%)
Critical	31	Grande Prairie (10; 32%)

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Physical vulnerability scores for telecommunication infrastructure based on standard deviations from the mean ranging from < 1 to > 1, had a distribution that only accommodated four classes (Fig. 4; Table 3): low, moderate, high, and critical. Fifteen (8.06%) of the towers were classified as low, 74 (39.8%) as moderate, 66 (35.5%) as high, and 31 (16.7%) of the 186 total towers were classified as critical with respect to physical vulnerability to wildfire (Table 3). Again, the Grande Prairie Forest Area had the highest proportion of towers classified as critical, with 10 of 31 (32%) towers classified with critical physical vulnerability to wildfire (Table 3). In contrast, the Lac La Biche Forest Area had the greatest proportion of towers with low (53%) and moderate (29.7%) physical vulnerability (Table 3).

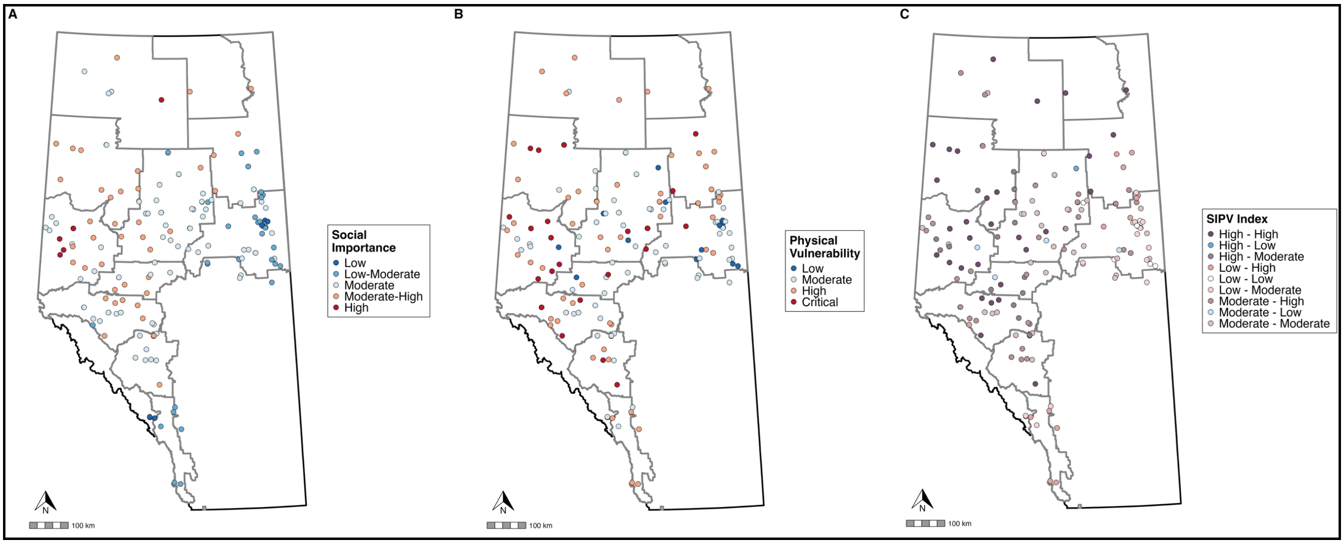

Figure 4: (A) Social Importance rating, (B) Physical vulnerability rating, and (C) Bivariate index classification of telecommunications towers in the Forest Protection Area (FPA) of Alberta. Towers with extreme wildfire exposure (n=186) identified by Kuiper and Beverly (2025) **were assessed. Colour ramp denotes (A) Social Importance Index class, (B) Physical Vulnerability Index class, and (C) combined Social Importance and Physical Vulnerability (SIPV) Index computed from individual ratings in (A) & (B).**

A bivariate classification was developed to represent the intersection of social importance and physical vulnerability of telecommunication infrastructure to wildfire (Fig. 4; Table 4). Over one fifth of towers (n = 22%) were classified with moderate levels of both social importance and physical vulnerability. A similar proportion of towers (21.5%) had moderate social importance and high physical vulnerability. Slightly fewer towers (n=34 or 18%) had high levels of both social importance and physical vulnerability, and 9 of these are located in the Grande Prairie Forest Area.

Table 5. Tower frequency by Social Importance and Physical Vulnerability (SIPV) Index classifications and associated mean ratings of social importance and physical vulnerability.

Class	Count	Mean SI Rating	Mean PV Rating	Most Common Forest Area (Count)
Low Social – Low Physical	8	-2.51	1.75	Lac La Biche (7)

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Moderate Social – Low Physical	6	-0.198	1.75	Slave Lake (2)
High Social – Low Physical	1	2.05	1.75	Slave Lake (1)
Low Social – Moderate Physical	18	-2.22	2.18	Lac La Biche (14)
Moderate Social – Moderate Physical	41	-0.171	2.10	Slave Lake (15)
High Social – Moderate Physical	15	3.08	2.15	Grande Prairie (4)
Low Social – High Physical	23	-2.52	2.67	Calgary (9)
Moderate Social – High Physical	40	-0.107	2.78	Slave Lake (9)
High Social – High Physical	34	2.42	2.94	Grande Prairie (9)

4 Discussion

The objective of this research was to rate telecommunications infrastructure with respect to both social importance and physical vulnerability to wildfire. The Social Importance and Physical Vulnerability (SIPV) Index provides a novel framework for assessing wildfire-related risks to telecommunication infrastructure, offering a nuanced understanding of which telecommunication towers should be prioritized for protection and mitigation in the context of critical infrastructure and wildfire management.

Our index identified 34 telecommunication sites classified as both critically vulnerable to wildfire and of high social importance. These towers represent the most at-risk infrastructure in terms of their susceptibility to wildfire and the potential societal impact of their loss. The concentration of these highly vulnerable towers in the Grande Prairie Forest Area highlights a hotspot of concern, likely due to a combination of high fire exposure, extensive road networks and anthropogenic development, and limited telecommunication infrastructure redundancy. Slave Lake is another notable Forest Area that shows higher than average social importance and physical vulnerability. While not as critical as telecommunications infrastructure in the Grande Prairie Forest Area, the infrastructure in Slake Lake similarly lacks redundancy with the presence of scattered and isolated infrastructure, increasing the risk of communication disruptions.

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Beyond these extreme cases, our analysis also identified a substantial number of towers (n = 41) in the moderate social importance and moderate physical vulnerability classification. Although these towers may not be a top priority, their SIPV classification highlights the need for a broader, tiered approach to response prioritization and proactive mitigation. This reinforces that structure protection strategies cannot solely rely on physical vulnerabilities to fire but must also consider the functional role that an asset may play in society (Zimmerman, 2001).

The SIPV Index can directly inform fire management and infrastructure protection strategies in several ways. Agencies can use the index to prioritize response resources during active wildfire incidents by focussing suppression efforts towards critically vulnerable, high importance towers. In areas where viable fire pathways (i.e., directional vulnerability) and fire exposure are high, mitigation efforts could be focused on fuel management such as targeted vegetation clearing or creating containment lines and fuel breaks to reduce potential fire transmission along high exposure pathways. Additionally, the SIPV Index can inform strategic placement of new telecommunication infrastructure to improve network redundancy in high-risk areas, potentially reducing the impact of tower loss on emergency communications.

The inclusion of slope and suppression capability as important factors indicative of a communication tower's physical vulnerability to wildfire can hopefully strengthen fuel-based fire exposure assessment when utilized for at-risk infrastructure identification, and in tandem, become a stronger index in terms of a tool for resource allocation optimization. Slope and suppression capability play a role in influencing fire spread and behaviour (Butler et al., 2007; Mandalapu et al., 2024; Papathoma-Köhle et al., 2022; Wagner, 1988) and are particularly relevant to telecommunications infrastructure, which are prioritized for suppression action and often located in upslope positions. By including slope and suppression capability in the SIPV Index, along with fuel-based indicators of potential fire transmission (i.e., exposure and directional vulnerability) we have provided additional insight into tower vulnerabilities. Some infrastructure may be in areas of high fire exposure, but if they are in close proximity to suppression resources and have limited viable fire pathways, the overall vulnerability may be diminished.

Socially relevant indicators, such as redundancy and coverage of anthropogenic features, helped to identify towers that could significantly disrupt communications in densely populated or high-traffic areas, should they be disabled by wildfires. This is particularly relevant in remote or underserved regions of the province where communication networks are limited and serve a vital role in communication and emergency coordination (Carreras-Coch et al., 2022; McMahon and Akçayır, 2022). Recent wildfire events in the Northwest Territories, Canada and Maui, USA have demonstrated the consequences of losing telecommunications or vital communications infrastructure during wildfire evacuations (CBC News, 2024; Kelly, 2023).

The SIPV Index provides a practical and adjustable framework for characterizing the vulnerability and societal significance of telecommunication infrastructure, enabling prioritization of wildfire mitigation efforts for critical infrastructure. Mitigation and fire prevention efforts can include vegetation clearing, fuel reduction, and inspection or enhancement of the structural integrity of infrastructure that has already experienced any interactions with wildfire (Butler et al., 2014; Zamanzadeh et al., 2024). This approach supports more targeted investment of resources in infrastructure protection, telecommunication network expansion, and emergency preparedness planning. As the risk of wildfire occurrence increases under changing climatic

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conditions, we hope that the SIPV Index can assist in supporting adaptive wildfire management, emergency management, and telecommunication network resilience.

Several limitations of our approach could be improved through future study. Equal weighting of the physical vulnerability indicators that we used differs from some previous research (Andersen and Sugg, 2019; Papathoma-Köhle et al., 2022), and may not fully reflect the complex interactions between variables. Onsite visits to vulnerable telecommunication sites should be conducted to verify data assumptions and confirm physical vulnerabilities identified in this study. Previous vulnerability indices have included socioeconomic indicators of vulnerability (Andersen and Sugg, 2019) or physical building materials as indicators of fire vulnerabilities (Papathoma-Köhle et al., 2022), inclusion of similar indicators may further contribute to our index; however, the construction materials of telecommunication infrastructure and equipment is more homogenous compared with residential building materials. Therefore, the inclusion of these attributes as variables will not change the resulting index ratings or impact the assessments between towers. However, future research into infrastructure redundancy and cost-effective risk mitigation strategies could enhance the practical application of the SIPV Index.

5 Conclusion

Results of the individual and combined indices revealed high fire vulnerability, low telecommunication resilience, and high societal reliance on the telecommunication infrastructure and communications network across the northern portion of the FPA in Alberta. This study and the results highlight the variation of fire vulnerability and societal importance of telecommunication across Forest Areas and underscores the importance of evaluating vulnerability from diverse perspectives. The Grande Prairie Forest Area was identified as the most critical in terms of tower vulnerability with 83% of the towers classified as high in the social importance index and 32% of towers rated critical in the physical vulnerability index. Additionally, Grande Prairie contained 26% of the towers within the high social importance and high physical vulnerability classification of the combined SIPV Index.

Our findings provide fire management agencies and telecommunication providers in Alberta with a practical tool for prioritizing mitigation and response efforts. The SIPV Index can help identify high priority infrastructure where fire exposure can be reduced through fuel management strategies such as fuel reduction in the form of extending clearings or containment lines and fuel breaks to modify fire exposure and directional vulnerabilities. Factors like slope and suppression capability cannot be modified, exposure and viable fire pathways can be addressed with fuel management. Social importance indicators, such as redundancy in coverage overlap and backup towers, can be addressed by installing new infrastructure in critical or high traffic areas. Future research should explore the feasibility and economic implications of infrastructure investment to enhance the resilience of the telecommunications network in relation to wildfire. Additionally, the SIPV Index could be adjusted to account for regional differences by customizing the input variables or changing the weighting factors and classification thresholds. The SIPV Index can also be adapted for other types of vital infrastructure such as electrical utilities or critical supply chains by incorporating relevant vulnerability indicators specific to those assets and the scale of service they provide.

In conclusion, this research highlights the need for robust and proactive fire mitigation and telecommunication network expansion across the wildfire-prone regions of the FPA. By proactively and systematically addressing the vulnerabilities of our telecommunication network, the province and fire management agencies can further enhance public safety, emergency preparedness, and build resilience in the systems that support our society. The SIPV Index provides a resource for advancing wildfire mitigation strategies and infrastructure protection planning in fire-prone landscapes.

Data availability

Data will be provided by the corresponding authors upon request.

Author contribution

CK contributed to writing – review & editing, writing – original draft, visualization, validation, software, methodology, Investigation, formal analysis, data curation, conceptualization. JB contributed to writing – review & editing, supervision, resources, project administration, methodology, funding acquisition, conceptualization.

Competing interests

The authors declare they have no conflict of interest.

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