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Community Risk and Resilience to Wildfires: Rethinking the Complex Human–Climate–Fire Relationship in High-Latitude Regions

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Abstract: Community risk and resilience to high-latitude wildfires has received limited conceptual attention, with a comprehensive, integrated framework that unpacks the complex human–fire–climate relationship in high-latitude environments largely missing. In this paper, we use insights from both the climate change adaptation and disaster risk reduction literature to build a conceptual framework to understand the factors and dynamics of risk and resilience to wildfires at the community level in high-latitude regions. Using an illustrative case study, the framework demonstrates how unique social and ecological features of high-latitude communities elevate their risk of wildfires and emphasizes the need to think holistically about the different spatial–temporal interactions and interdependencies between fire, humans, and climate in these regions. We find that remoteness, indigeneity, subsistence-based activities, and colonial practices, along with accelerated climate warming, are notable features influencing community risk and resilience to wildfires in high-latitude regions. This framework can help unravel the complex nature of wildfires, guide stakeholders through each phase of the disaster process, and facilitate the development and design of wildfire-related policies and strategies in high-latitude regions.

Keywords: climate change; wildfire; risk; resilience; adaptation; vulnerability; disaster; conceptual framework

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1. Introduction

Many regions globally are experiencing increasingly extreme wildfire seasons. In North America, Australia, and parts of the Arctic, for example, observed wildfires are more intense and destructive than in the past [1,2]. These increases in the magnitude and severity of wildfires have been largely attributed to the complex interplay between climatic and non-climatic drivers, including ongoing and future human-caused climate change [3]. Climatic factors include seasonal temperature, humidity, precipitation, and lightening, while non-climatic factors include landscape patterns, vegetation types and structure, and human dynamics (e.g., fuel and land management practices, agricultural and timber activities, cultural events, land use) [4–6]. The way through which these (non-)climatic factors interact over space and time is considered a challenging problem [7], yet one that is of particular importance for minimizing the negative impacts and maximizing the positive outcomes of wildfires.

Wildfires pose unique challenges in high-latitude regions, defined here to include roughly all boreal and tundra areas above 50° N [8]. Some of the most notable challenges include (1) increasing values-at-risk [9], (2) reduced fire suppression effectiveness [10], (3) increasing fire-management costs [11,12], (4) significant physical and mental health

impacts [13], and (5) decreased ecosystem resilience [14,15], all of which could ultimately slowly progress towards achieving the United Nations Sustainable Development Goals and other environmental goals [16]. Although these challenges are not necessarily new, the nature of the challenges is fundamentally different than in mid-latitudes. High-latitude regions (especially the Arctic and sub-Arctic) will see some of the most rapid and extreme warming globally (a rate approximately three times the global average), with considerable cascading impacts on wildfire regimes, permafrost, and biodiversity [3]. Additionally, wildfires in the more rural and remote high-latitude regions are often not immediately suppressed and are usually left to burn unless valuable assets are threatened, resulting in large areas burned and in the release of large amounts of particulate matter (PM2.5) [17,18]. Furthermore, many communities are located in rural, sometimes remote, areas with limited access to emergency services and fire management infrastructure, where traditional fire knowledge is often undermined by socio-political structures [19,20]. In fact, high-latitude communities have limited decision-making powers, with wildfire prevention, mitigation, and response mostly regulated by regional and national authorities [21,22]. Hence, wildfire-management techniques adopted in lower latitudes might not work in higher latitudes given the changing climate, the magnitude of wildfires, and the limited preparedness of local communities, requiring alternative management strategies tailored to the local and regional context [8,23].

Reflecting this, there has been increasing interest within the wildfire and climate change adaptation community in understanding human–climate–fire relationships that create and shape risk and resilience in high-latitude regions [24–26]. Notwithstanding, while these efforts have highlighted the role of multiple factors governing risk and resilience (e.g., fire management policies, risk perceptions), few capture the nature of these interactions holistically, particularly at the community level, with many focusing only on specific aspects of risk and resilience [27]. For example, studies have overlooked how compounding (e.g., droughts, heatwaves) and cascading risks (e.g., water runoff, changes in biodiversity dynamics) associated with wildfires consecutively influence how communities experience, cope with, and plan for wildfires. This may ultimately lead to incomplete and fragmented approaches to fire policy and management, resulting in solutions that may be of limited use on the ground.

In this paper, we propose a conceptual framework to understand the factors and dynamics creating and sustaining community risk and resilience to wildfires in high-latitude regions. We integrate resilience and risk framings into a coherent structure based on the disaster risk reduction cycle, drawing upon the literature on natural hazards, disaster risk reduction, fire social science, wildfire ecology, and climate change vulnerability and adaptation. Structuring our framework by integrating risk-resilience approaches into the disaster risk reduction cycle, we seek to (1) create an enhanced understanding of the spatial–temporal interactions between climate, fire, and humans in high-latitude contexts; (2) provide a systematic way of breaking down the complexity of wildfire management into manageable pieces, which can then facilitate decision-making for adaptation; and (3) pinpoint where key mismatches and gaps exist to facilitate future research efforts and collaborations. For the purposes of this paper, wildfires are defined, consistent with UNEP [28], as "...an unusual or extraordinary free-burning vegetation fire which may be started maliciously, accidentally, or through natural means, that negatively influences social, economic, or environmental values". We also focus our framework on the community scale, noting it has applicability in diverse global contexts.

2. Setting the Scene: Linking Risk, Resilience, and the Disaster Risk Reduction Cycle

The concepts of risk, resilience, and the disaster risk reduction cycle have been used, defined, and related in various ways in the literature. We understand risk as the combination of hazard, exposure, and vulnerability, thereby following the general disaster and adaptation literature [29,30]. We also use resilience to think about the capacity or ability of communities to persist, recover, adapt, and/or transform in the face of hazards [31,32]. Both

vulnerability and resilience are linked here through the component of coping capacity [33] and are considered related yet different [34]. Moreover, risk and resilience are seen in this paper as dynamic and contextual elements that are determined by the continuous interaction of multiple social and natural factors; these factors can be either fast or slow in their onset and can derive from sources both exogenous and endogenous to the community [35]. In Table 1, we define each of the conceptual elements that are adopted in this paper.

Table 1. Definitions used in the conceptual framework.

Components of the Framework	Definition	References
Risk	Potential for adverse consequences for human or ecological systems. It results from both the dynamic interactions between hazard with the exposure and vulnerability of the affected system, and from the potential for responses not achieving the intended objective(s), or from potential trade-offs or negative side-effects.	[30,36]
Resilience	Describes the capacity of individuals, communities, and systems to persist, cope, adapt, and transform in the face of stress and shocks. It is a function of the combined result of coping, adaptive, and transformative capacities, which in turn lead to persistence, incremental adjustments, or transformational responses in the face of environmental change	[37,38]
Hazard	Possible, future occurrence of natural or human-induced (wildfire) events that may have adverse or beneficial effects on a system, including, amongst others, loss of life, injury, loss of infrastructure, or increased habitat regeneration.	[39,40]
Exposure	Presence of people, livelihoods, species or ecosystems, environmental services and resources, infrastructure, or economic, social, or cultural assets in places where hazard events (i.e., wildfires) may occur.	[41,42]
Sensitivity	Describes pre-existing conditions and characteristics of human beings, livelihoods, infrastructure, and environmental assets and services within a system that govern its susceptibility to the effects of an exposure; it is tightly related with vulnerability	[43,44]
Vulnerability	The propensity or predisposition to be adversely affected by a hazard. It is a component of risk and is based upon a system's sensitivity or susceptibility to harm and lack of capacity to cope.	[45,46]
Adaptation	The practice of implementing or utilizing adaptive capacity to alter behaviour or overcome drivers to decrease risk, to cope with possible impacts and exploit beneficial opportunities.	[35,47]
Transformation	A change in the fundamental attributes of human systems in anticipation of future hazards and its impacts. It is adopted at a much larger scale, that are truly new to a particular region or resource system, and that transform places and shift locations. It results from implementing or utilizing transformative capacity.	[47–50]
Coping capacity	Ability of a system to draw on skills, resources, and experiences to immediately react to, cope, and reduce the adverse effects of experienced hazards, in this case wildfires; it is a component of resilience as used by [17].	[51,52]
Persist(ence)	Capacity of a system to absorb disturbance(s) and still maintain essentially the same structure, functions, feedbacks, identity, and relationships between variables. Also used in the literature to describe the ability of people and communities to recover or 'bounce back' to pre-disaster conditions.	[53–55]
Adaptive capacity	Refers to the ability or potential of a system to adjust or make incremental changes in response to exposure/vulnerability. Adaptations are manifestations of adaptive capacity, and has been also used as a component of resilience within the wider literature. Adaptive capacity does not, however, necessarily result in adaptation; a community may have high adaptive capacity but not adopt adaptations to changing conditions [25].	[51,56–58]

Table 1. *Cont.*

Components of the Framework	Definition	References
Transformative capacity	Creation of fundamentally new systems through profound shifts in human systems when existing conditions are untenable. It goes beyond incremental changes that maintain the status quo, bringing deeper changes to a system than does adaptation. Transformative capacity is also referred in the literature as 'transformability'.	[47–49]
Endogenous factors	Factors internal to the system that govern its risk and resilience (e.g., local demographic patterns, livelihoods) and determines how systems are able (or not) to change its nature; endogenous factors are determined by both fast and slow moving factors.	[59,60]
Exogenous factors	Factors external to the system that govern its risk and resilience (e.g., regional governance systems, global climate change) and determines how system are able (or not) to change; exogenous factors are determined by both slow and fast factors.	[59,60]
Fast moving factors	Variables that change on daily, seasonal, and interannual time scales and result in rapid variations in a system's vulnerability and resilience (e.g., pest outbreaks in forests, monthly changes to wildlife dynamics). Fast variables are also called fast-moving attributes, and can emanate from both exogenous and endogenous factors.	[61–63]
Slow moving factors	Slow variables describe trends that are constant over multiple years to decades, such as global climate change or changes in socio-political structures; they result in gradual change to a system's risk and resilience. Slow variable can emanate from both exogenous and endogenous factors.	[61–63]
Compound events	Describes the combination of single extreme events or multiple coincident sequential events that contributes to a system's risk-resilience. Compound events can be broadly grouped into (i) preconditioned events, where a weather-driven or climate-driven precondition aggravates the impacts of a hazard; and (ii) multivariate, whereby multiple hazards and/or drivers concurrently or successively (the latter known as cascading event) occur and exacerbate hazards impacts on a system.	[64–66]

In this framework, we also link risk and resilience with the disaster risk reduction cycle. The interpretation we make in this paper regarding risk, its associated elements, and resilience is complementary to the different phases of the disaster risk reduction cycle, which, broadly speaking, is a function of three interlinked yet separate over-arching stages: pre-disaster, during, and post-disaster event. Indeed, the concepts of risk and resilience have strong similarities with the terminology and notions used in the cycle [67–70]. During and post-hazard actions, for example, are consistent with the notions of resilience in the climate adaptation literature [37]. Similarly, the pre- and during-disaster phases are strongly related to the concept of risk as currently understood in the adaptation community [30]. Although some have questioned the use of these concepts [71,72], this interpretation of risk, resilience, and the disaster risk reduction cycle remains useful to capture the interactions between human and natural systems [73,74] and bridge disciplinary and stakeholder divides [75,76]. The linkage between risk, resilience, and the disaster risk reduction cycle is particularly helpful to (1) expand the range of potential responses available, which would be otherwise missed if risk and resilience were approached separately, and (2) recognize both longer-term system drivers and nuanced, contemporary and local socio-economic realities [33,34,77]. This linkage can also contribute to the harmonization of the adaptation literature with that of related disciplines, particularly with the disaster risk reduction community [30,78], and overcome the existing silos between the two disciplines, which is argued to be key in ensuring an adequate and appropriate distribution of funds [79].

3. Conceptual Framework for Understanding Community Risk and Resilience to High-Latitude Wildfires

Based on our interpretation of risk, resilience, and the disaster risk reduction cycle (Section 2), we propose a framework that is organized into three broad stages (Figure 1):

- The ex ante (before a wildfire) stage is focused on setting the stage for characterizing wildfire risk and resilience, which is considered here to be a combined result of a community's initial exposure, vulnerability, and the ability to anticipate, prepare, and plan for future wildfire events (i.e., adaptive and transformative capacity).
- The during wildfire stage relates to understanding the characteristics of the hazard and the ability of a community to cope with and survive the impacts of wildfires (coping capacity).
- The ex post stage of the framework relates to how risk and resilience change after a wildfire hits a community. This stage acknowledges that experiencing a wildfire can trigger major, sudden social transformations in the community that inevitably and often lead to changes in the nature of risk and resilience [80]. This is particularly pertinent in high-latitude regions, where wildfires are, and will continue to be, a natural feature impacting communities, especially in fire-prone boreal forests [81]. For this reason, we herein classify risk and resilience in two separate tiers, based on whether the community has already experienced a wildfire: '$risk_1$' and '$resilience_1$' as well as '$risk_2$' and '$resilience_2$'. $Risk_1$ and $resilience_1$ capture the conditions of a community both before and during a wildfire, whereas $risk_2$ and $resilience_2$ reflect the impacts that wildfires have on the community's exposure/vulnerability and its capacity to persist, adapt, or transform to future potential wildfires. The terminology, such as adaptive capacity or exposure, is also classified according to these tiers.

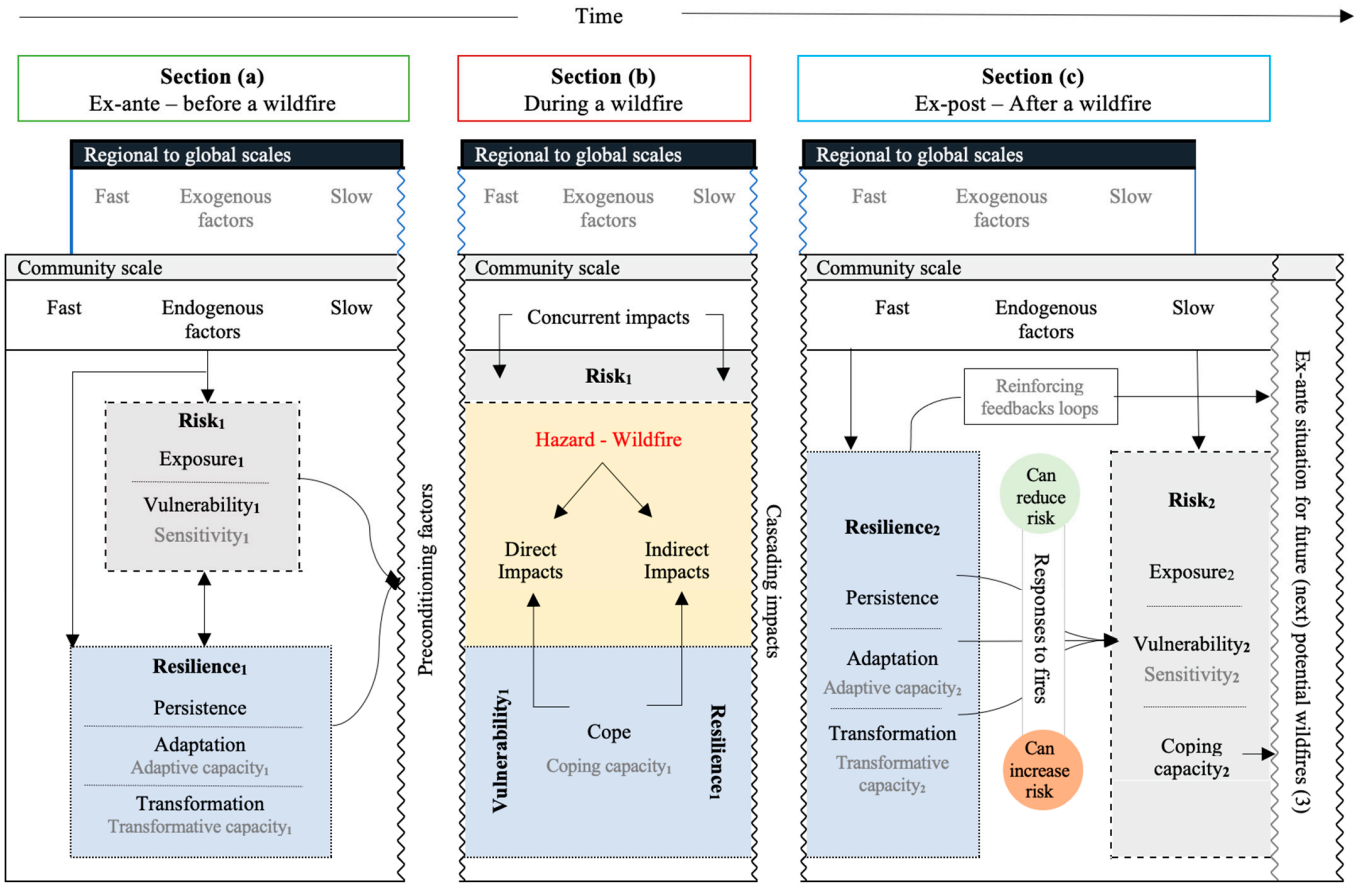

Figure 1. Overview of the conceptual framework. Section (**a**) shows the elements and dynamics of community risk and resilience before experiencing a wildfire, section (**b**) is during, and section (**c**) is after a wildfire. Figures 2–4 below provide more details for each stage of the framework (ex ante, during, ex post).

Each stage of our framework is regulated by multiple interacting fast- and slow-moving internal (endogenous) and external (exogenous) factors [63,82]. These vary between communities over space and time and often create different levels of risk and resilience among communities. For example, high-latitude communities, within and between nations, have different socio-economic development statuses (e.g., urban–rural) that have a variable magnitude of impact on the level of resources available to manage wildfires and potential impacts [83]. These are not mutually exclusive, such that factors influencing community risk can also determine its resilience and the extent to which impacts are experienced or managed [35,37]. Table 2 provides examples of factors affecting wildfire risk and resilience in high-latitude communities, noting that they should not be considered exhaustive as they are context-dependent. We also note that each of the factors included in our framework is subject to uncertainties, including, for example, the future development of the wildland–urban interface, the evolution of subsistence-based activities, and the efficacy of fuel treatments [84]. The next sections discuss, in greater detail, these factors and how they vary across the three stages of the framework.

Table 2. Factors regulating wildfire risk and resilience at community level in high-latitude regions. Types are distributed into five categories: natural, place, socio-economic–demographical, institutional, and cultural. Symbols indicate decreases (↓), increases (↑), decreases and increases (△), or unknown effect (?) in community risk and resilience to wildfires.

Type	Effects on Resilience	Effects on Risk	References
Natural environment			
Climate (and its short-term manifestation, weather)	↓	↑	[85–95]
Fuels (soil and vegetation types)	?	△	[88,89,91,93–96]
Ignition sources (e.g., lighting, human-caused)	?	↑	[91,93,97]
Topography	?	△	[85,91,93–95,98]
Place			
Settlement location, remoteness	↓	↑	[13,83,85,99–106]
Place attachments	△	△	[13,105,107–113]
(Previous) experiences with wildfires	↑	△	[13,110,114,115]
Infrastructure and access to resources	△	△	[85,99,100,106,110,115,116]
Social networks and learning (e.g., community support)	↑	↓	[13,99,105,111,113,117]
Public perceptions, attitudes, awareness, and mistrust	△	△	[13,99,106–108,110,114,115]
Socio-economic–demographical			
Demography (age, gender, race, ethnicity), population density	△	△	[85,104,105,108,111,115,118–122]
Livelihood (hunters, farmers, loggers, etc.)	↑	↑	[13,99,105,108,111,114,117,123–126]
Economic status and community income	△	△	[99,105,106,111,113,116,119]
Health and mental conditions (e.g., chronic diseases)	↓	↑	[105,106,111,113,116,119,122]

Table 2. *Cont.*

Type		Effects on Resilience	Effects on Risk	References
Institutional				
	Colonialism, assimilation policies, land dispossession, racism, and structural violence and disparities	↓	↑	[103–105,113,127,128]
	Fire and fuel management practices and policies (including historical, past, and current practices)	△	△	[102,105,106,108,111,113,116,117,120,129–131]
Cultural				
	Traditional fire use and knowledge	↑	↓	[106,117,127,131–133]
	Cultural practices, beliefs, and rituals	△	△	[13,105,106,112,127,131–133]

3.1. The Ex Ante Stage: Community Risk and Resilience before a Wildfire Event

Figure 2 details the key building blocks of this stage. Before a wildfire takes place, high-latitude communities are at $risk_1$ depending upon two interconnected factors: (1) community exposure and (2) (social) vulnerability. Exposure and vulnerability are broadly determined at this stage by the characteristics of climatic conditions (and its short-term manifestation, weather), the nature of the community under consideration, and the natural features present within or nearby the community that make a fire more likely to happen. Climate- and weather-related characteristics include the magnitude, frequency, duration, spatial dispersion, and novelty of lightning activity and fire weather conditions (i.e., temperature, humidity, wind, precipitation), which, in turn, influences landscape flammability, fuels, and fuel conditions (moisture), i.e., wildfire severity [93,94]. The nature of the community largely concerns its location and socio-demographic, economic, institutional, and cultural structure. For example, being situated within or near a matrix of flammable vegetation (i.e., wildland–urban interface areas), particularly in fire-susceptible regions in the boreal zone, increases the exposure of communities and the degree to which impacts are suffered [101]. Similarly, other distinctive factors of many high-latitude communities, including remoteness, socio-economic inequalities, limited access to fire infrastructure and resources (e.g., wildland–urban interface structure density data and mapping, computational and mathematical models), and a lack of fire management strategies, elevate their risk to wildfires [100,106,116]. Lastly, risk is further determined by the physical structure of the landscape present within or nearby the community (i.e., topography, forest canopy, geological substrate), which has an effect on ignition patterns, fire spread, and local fire weather [94,95,98,134].

Moreover, the capacity and ability of a community to anticipate, prepare, and plan for (potential) future wildfires—also referred to as $resilience_1$—further determines whether a community may be at a higher risk of experiencing the negative impacts of wildfires [53]. The adaptive and/or transformative capacity of a community is largely moderated by multiple economic, demographic, cultural, social, and political factors that are characteristic of human systems. These factors include past and current fire policies, personal experiences with wildfire, and stakeholders' understanding of the role of fire as a landscape process [108,110,125]. For example, colonial policies in Canada and Alaska have often disrupted the transmission of traditional fire knowledge and reduced the use of fire by local communities in the landscape, leading to decreased resilience and increased risk due to the accumulation of fuels [20,127]. The combined result of adaptive and transformative capacity can lead to the adoption of both long- and short-term responses, including policies that address the potential cascading effects of wildfires on communities (i.e., after) or even the improvement of evacuation systems that would help a community cope during a wildfire

(i.e., during). These responses can act on various components of the society–environment interaction, including measures that change the biophysical system (e.g., prescribed fires, removing small, shade-tolerant trees in low-lying forests) and/or the human system (e.g., fire infrastructure improvements, changes in livelihoods). Responses implemented at this stage are categorized into the so-called prevention (including mitigation) or anticipatory (proactive or ex ante) responses and can directly influence the severity of future wildfire events [135].

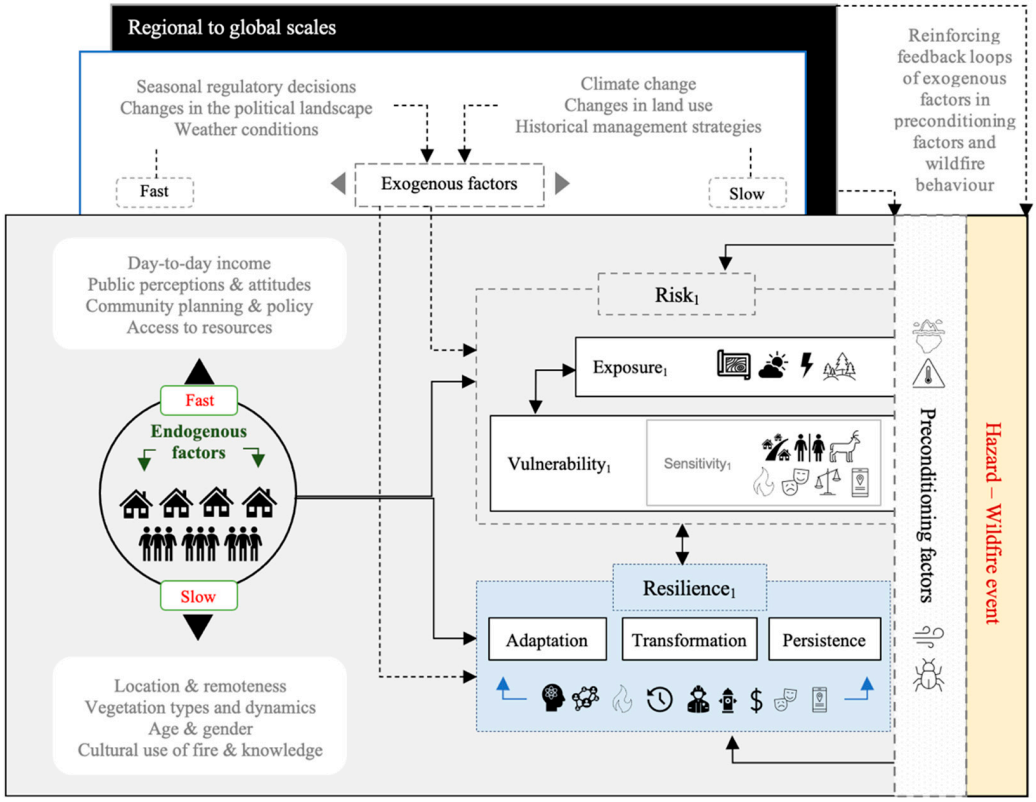

Figure 2. Conceptual framework for understanding the factors and dynamics of community risk, vulnerability, and resilience to wildfires in a high-latitude context before a wildfire. Refer to Table 2 for related icons. Solid lines represent the endogenous effects, and dashed lines represent the exogenous effects.

Ultimately, preconditioning factors—that is, weather-driven or climate-driven events that precede a wildfire—are important for understanding high-latitude wildfire risk and resilience holistically [64,136]. These factors can diminish the ability to cope, manage, and respond to wildfires and, thus, exacerbate a community's risk and impacts. The outbreak of mountain pine beetle in Western Canada, for example, has increased the risk of wildfires in the region; indeed, analyses indicated that the magnitude of the 2017 and 2018 wildfires in British Columbia might have been exacerbated by such an insect epidemic [137,138]. Long-lasting heat waves, which more often than not precede intense wildfire seasons, can also trigger permafrost thaw that may weaken crucial infrastructure necessary to respond to a potential wildfire as well as aggravate the effects of air pollution during a wildfire [139,140]. These stressors can involve many more events, including floods, strong winds, and droughts, which can be felt either through direct effects on the community (by cascading impacts from other local events) or by processes emanating from other locations (e.g., when a flood in another jurisdiction damages energy infrastructure, causing blackouts and financial and human impacts). Some of these preconditioning factors can be slow in their onset (such as droughts resulting from changes in temperature and precipitation), while others occur suddenly (e.g., storms, floods).

3.2. During Wildfire Stage: Community Risk and Resilience during a Wildfire Event

In the event of a wildfire, community risk$_1$ and resilience$_1$ are largely modulated by the interaction between (i) the hazard's characteristics (measured by the magnitude, intensity, location, and duration) and (ii) the coping capacity of a community. This interaction determines the extent to which a wildfire may result in negative (or positive) economic, financial, environmental, and social impacts, in addition to determining how wildfires are experienced and whether the community is able to respond (Figure 3).

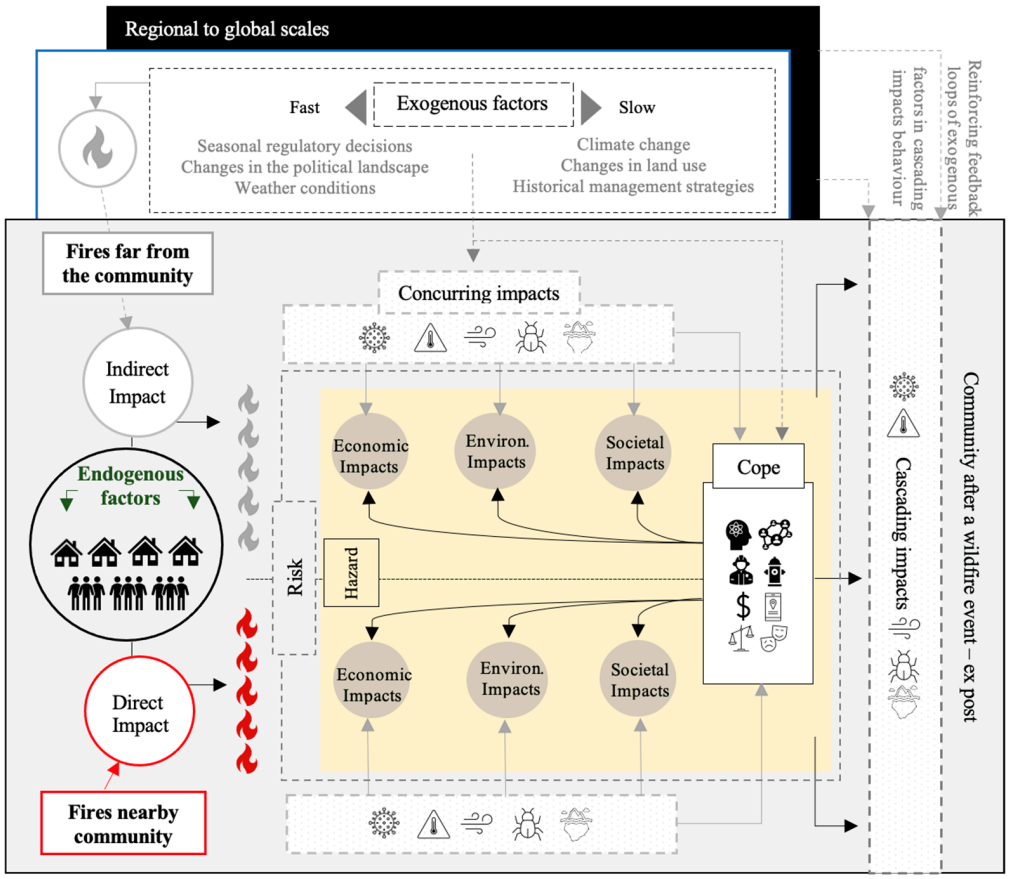

Figure 3. Conceptual framework for understanding the factors and dynamics of community risk, vulnerability, and resilience to wildfires in a high-latitude context during a wildfire. Refer to Table 2 for related icons. Solid lines represent the endogenous effects, and dashed lines represent the exogenous effects.

The characteristics of the hazard should be fully considered to comprehensively understand the nature of the risk that a community faces. Indeed, depending on the geographical location, magnitude, intensity, and duration of the wildfire event, community risk can take many different forms. On the one hand, there are the direct impacts of wildfires, which refer to wildfires that occur in the vicinity of a community and that pose an immediate threat to people and buildings. Conversely, the indirect impacts refer to wildfires that take place in other jurisdiction(s), yet with an effect on distant communities, particularly through water and smoke pollution and infrastructure disruption [4,141]. Both the indirect and direct impacts of wildfires can result in negative impacts such as loss of life, infrastructure, and properties, as well as ecological benefits from improved habitat heterogeneity, all of which can impact people's psychological, physical, and financial well-being [104,119]. The extent to which these impacts are experienced by community members is highly dependent upon (i) the severity of the wildfire and (ii) the socio-demographic characteristics of the community (see Section 3.1). Furthermore, concurrent impacts, whereby multiple hazards

concurrently occur and interact, can exacerbate wildfire impacts on communities and reduce the ability of a community to react to and cope with wildfires. These stressors may involve events such as heat waves, droughts, strong winds, or forest insects and diseases (e.g., pine beetle) and may impact, among others, crucial infrastructure as well as firefighting suppression efforts [142,143].

Whether a community can immediately respond to a wildfire and related multivariate stressors in a way that reduces their negative impacts and survive will depend on its coping capacity$_1$. Coping capacity refers to a community's ability or capacity to draw on skills, resources, and experiences to immediately react to and cope with a hazard; it is influenced by community characteristics, including social, economic, and demographic factors (e.g., economic wealth, social networks, infrastructure, or experience with previous risks) and broader exogenous factors such as national fire policies [104,105,131]. These factors, in turn, determine the extent to which a community can implement responses during a wildfire, including evacuating the community or halting all outdoor activities. Coping capacity can vary over time in response to social, economic, political, and future environmental changes and can also be undermined by the effects of cascading impacts from other hazards. Approaches that help ensure effective coping responses when a wildfire does occur would fall into the preparedness category of the cycle.

3.3. Ex Post Stage: Community Risk and Resilience after a Wildfire Event

The aftermath of wildfires can result in multiple changes to the short- and long-term risk$_2$–resilience$_2$ dynamics of a community (Figure 4). In the disaster risk reduction literature, this is often regarded as the best opportunity to drive change [144,145]. First, after a wildfire event, the direct exposure$_2$ of a community may be reduced, given that most fuels in the surrounding are likely to be consumed, thereby reducing the short-term risk of future wildfire events [146]. However, in boreal forests, wildfires might exhibit 'overwintering' behavior, in which they smolder through the non-wildfire season and flare up in the subsequent spring (i.e., 'zombie fires'), thereby resulting in different post-fire recovery trajectories [93,146,147]. Whether a wildfire exhibits overwintering behavior will depend upon the presence of deep organic soils, along with accelerated climate warming, extreme weather conditions, and large annual fire extent [93].

Second, experiencing wildfires—either directly or indirectly—can foster opportunities for communities to increase their ability and capacity to pursue incremental (adaptive capacity$_2$) or transformational (transformative capacity$_2$) responses. Following an event such as a wildfire, constraints that normally determine decision-making processes have been observed to dissipate due to changes in public opinion, awareness, and risk perception, leading to an enhanced ex post state of preparedness [148–150]. In Canada, for example, new behavioral patterns and habits emerged post-wildfire among decision-makers and the public, resulting in the adoption of community resilience-building measures such as the incorporation of Indigenous knowledge in decision-making processes and the creation of inter-community sharing networks [13,21,67]. Scholars, however, caution that this window of opportunity is open for a short period of time and that the ability or capacity of a community to take advantage of this and implement measures that reduce future vulnerability depends on (i) the extent of the damages experienced; (ii) their access to longer-term support structures; (iii) and their pre-existing social, cultural, economic, demographic, and political conditions [144,151]. In high-latitude regions, governmental constraints, including insufficient available funds, professional expertise, and a lack of urgency and public support, are key factors that can explain why change is elusive and why the level of community risk and vulnerability remain static over time or even increase after a wildfire [152].

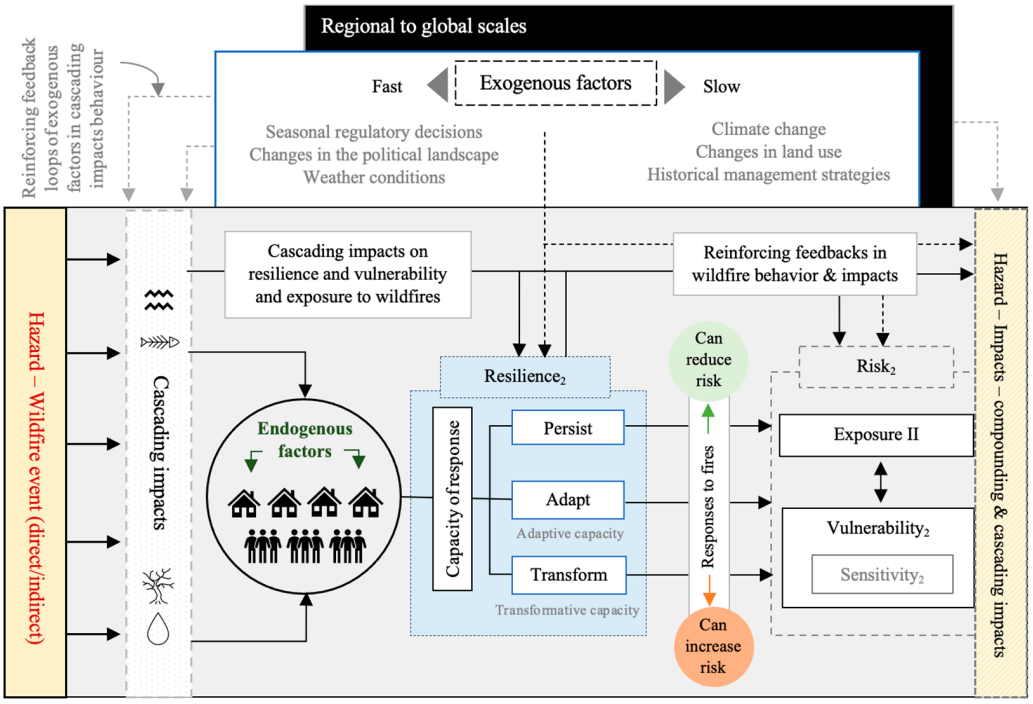

Figure 4. Conceptual framework for understanding the factors and dynamics of community risk, vulnerability, and resilience to wildfires in a high-latitude context after a wildfire. Solid lines represent the endogenous effects, and dashed lines represent the exogenous effects.

Third, the cascading impacts of wildfires may also negatively impact a community toward future events. Wildfires can exacerbate the risk of burned landscapes to flooding, landslides, and debris flow, increasing the exposure of communities to these hazards one or two years after a major wildfire [153]. For example, post-wildfire impacts were considered a contributing factor in driving runoff and debris flows during the devastating floods and landslides that impacted southern parts of British Columbia (Canada) in 2003 and 2021 [154,155]. Similarly, wildfires can disrupt carbon cycling and ecological interactions, triggering biome shifts and leading to deteriorating water quality and changing snowpacks during subsequent seasons [156]. This, in turn, can cause, amongst other things, food insecurity, health issues triggered by a lack of sanitation, human displacement, and the loss of social ties and a sense of place and cultural identity, along with road network damages, power and communication infrastructure disruption, and business activity interruptions [13,140]. Communities with network dependencies (e.g., transportation hubs), limited institutional and regulatory systems, limited sanitation services, an aging infrastructure, low incomes, and subsistence economies may be more exposed and sensitive to these cascading impacts [117,123] to the point that these factors can overwhelm a community's capacity to respond and recover (resilience$_2$), heightening the risk of crossing unknown response capacity tipping points [65].

4. Case Study Application of the Conceptual Framework

In this section, we use the community of Sebyan-Kyutol (Russia) as a case study example to illustrate the potential application of the proposed framework. This particular case study was chosen purposefully due to the authors' prior research with the community and also because it presents an excellent opportunity to highlight the concepts of risk and resilience in a region where the human dimensions of wildfires are not well understood [157]. This community was also selected because (1) it is located in one of the most wildfire-prone regions globally, (2) it is projected to experience some of the greatest increases in wildfire frequency and severity globally, and (3) it shares considerable similarities with other high-latitude communities (e.g., remoteness, indigeneity, subsistence-based livelihoods) [1,24,99].

Secondary sources, including governmental reports, journal articles, books, and newspapers, were used here to provide context and information on the community's wildfire risk and resilience.

4.1. Case Study Description: Sebyan-Kyuyol, Republic of Sakha

The community of Sebyan-Kyuyol is a rural, remote settlement located in the Kobyaysky ulus (Republic of Sakha, Russia). It is located 350 km from the administrative center of the Republic, Yakutsk, and it has a total population of 754 (2016) inhabitants, of which 89% belong to the semi-nomadic Lamunkhinsky Even people [158,159]. This Indigenous group lives in remote camps during different seasons and is highly reliant on traditional reindeer husbandry and hunting, berry picking, and other traditional industries associated with arts and crafts, which provide important food, nutrition, income, and cultural strength to the community [158,160]. The community is surrounded by the Verkhoyansk mountains, dominated by tundra vegetation (e.g., mosses and lichens), and characterized by harsh climatic conditions with frequent droughts and low precipitation levels [159,161]. Moreover, no road systems are connected with the community directly, nonwild food is expensive, employment and education opportunities are limited, and access to emergency services and fire management infrastructure are inadequate [159,162,163]. Community decision-making powers are being undermined by current policy and decision-making structures [163], and despite no wildfires having been recorded to directly affect the community so far, seasonal wildfires consistently occur throughout the region.

4.2. Application of the Framework to Sebyan-Kyuyol

To understand Sebyan-Kyuyol's wildfire risk and resilience using our framework, the first step is to characterize its initial exposure, vulnerability, and adaptive/transformative capacity by evaluating local threat conditions and the ability to adapt and transform. The ex ante exposure/vulnerability of Sebyan-Kyuyol derives from a combination of interacting climatic and non-climatic factors. Climatic factors include (i) local and regional weather patterns [164], (ii) climate-driven increases in the frequency and magnitude of extreme events [165], (iii) changing tundra vegetation [166], and (iv) increases in lighting activity and fire weather days [96]. Non-climatic factors relate to the community's mountainous location in a remote and ice-rich landscape [167,168]; the absence of highly flammable vegetation [166]; and socio-demographic and institutional factors, including limited traditional fire uses, indigeneity, livelihoods, and forest and fire management policies [159,166]. These factors also determine the adaptive and transformative capacity of the community. For example, climate-driven increases in the frequency and magnitude of extreme events, such as floods and permafrost thaw, are impacting critical infrastructure throughout the Republic that is necessary for responding to wildfires [169]. Similarly, current state support systems do not provide aid to Indigenous groups in the event of a wildfire, and the majority of wildfire adaptation policies overlook the role and needs of Indigenous peoples [163,170]. Indigenous people's ability to adjust subsistence practices based on traditional knowledge and existing sharing networks, however, increases resilience to wildfires [171].

The second step of our framework involves understanding the type of impact the community experiences from wildfires and its ability to cope with the impacts. While the Republic of Sakha is subject to frequent and severe wildfires (both natural and human-caused) during summer [166], the presence of less fire-prone tundra vegetation types within the community reduces the short-term likelihood of a wildfire impacting the community directly [161]. The frequent occurrence of wildfires in other parts of the Republic during summer, however, means that the community often experiences the indirect impacts of wildfires, particularly the increased air pollution caused by wildfire smoke [172]. During the 2021 summer wildfires in Siberia, for example, the air quality in the Republic was ranked among some of the worst worldwide, exceeding the recommended parameters of the World Health Organization [106]. Consequently, these smoke events have had significant impacts on the community's population, including disruptions to subsistence

activities [172]. Similarly, wildfires from southern parts of the Republic were documented to damage key transportation routes and negatively impact connectivity to other parts of the region, with consequences for food and fuel delivery [169]. The extent to which these impacts are felt in the community varies by gender, age, and indigeneity and is often exacerbated by the remote location of the community and its limited transport network [121,159]. People in the Republic of Sakha are nevertheless coping in different ways. Some have moved from the Republic to other regions of Russia until the wildfires are over; others have started social media campaigns locally to raise awareness and help firefighters with food supplies and inventory [106,121]. These responses are underpinned by traditional sharing and support systems, high learning capacities and strong traditional knowledge and local knowledge, limited ownership of equipment required for managing wildfires, and current fire management response practices [106,164,171].

The third step of our framework focuses on characterizing the aftermath of wildfires. In the context of Sebyan-Kyuyol, the ex post impacts of wildfires are based on the natural features of the landscape and the socio-demographic characteristics of the community. While the absence of nearby peatlands reduces the likelihood of smoldering fires [146], the community's semi-nomadic and traditional livelihoods increase its exposure/vulnerability to changes in key plant and animal species driven by wildfires burning in other parts of Sakha, making reindeer herding, berry picking, and hunting more difficult [117,172,173]. This situation, nevertheless, is expected to worsen with ongoing and projected climate change, which is increasing the availability of surface fuels and exacerbating the risk of the direct impacts of wildfires [8]. These impacts can cause permafrost to thaw near the community and lead to land subsidence, localized flooding, and the formation of lakes and wetlands, along with significant damages to infrastructure and human lives and livelihoods [174]. Given the mountainous location of the community, nearby wildfires can also lead to increased water runoff, erosion, and landslides, with the potential to contaminate key potable water sources [174]. Here, the community's lack of health and water treatment infrastructure exacerbates their risk of these cascading impacts [175]. Despite this, there is evidence showing that people throughout the Republic are not remaining static and are using social media to attract attention to the ex post impacts of wildfires [106,170]. This has been attributed to the combination of recent wildfire seasons and the discontent with how wildfires were managed and responded to by the government, and this was made possible by people's access to technology and strong support networks [106,170]. This activism caused the Russian government to increase its financial investments in fire suppression mechanisms and evaluate their role in managing wildfires, with consequences for community risk and resilience [170].

By focusing explicitly on the situation of the community before, during, and after a wildfire, our framework, if adopted, can help provide important insights into different aspects of Sebyan-Kyuyol's risk and resilience. First, the framework provides important insights into why and how the community is at risk of wildfires and illustrates the factors that govern the ability of the community to adapt and transform in the event of wildfires. Second, it distinguishes two types of wildfire impacts and how these result in different disruptions to the livelihoods and well-being of the community. Third, the framework reveals the types, likelihood, and magnitude of extreme compound impacts emerging from wildfires and highlights the ways people are responding to these impacts. This approach allows us to identify the factors that play a greater role in community risk and resilience and understand the weaknesses and strengths of Sebyan-Kyuyol before, during, and after a wildfire, facilitating the identification of adaptation gaps and needs. For example, the exposure/vulnerability of the community to the recurrent impacts of wildfire smoke every summer can be reduced by investing in ventilation systems that maintain indoor air quality [119]. Equally important, efforts can focus on improving firefighting, health, and water treatment infrastructure so the community can withstand future projected increases in wildfire activity near the community [117]. Implementing these responses in Sebyan-

Kyuyol would also likely increase the resilience of the community to other extreme climate events, including permafrost thaw, floods, or extreme temperatures [106,165].

5. Discussion and Conclusions

This paper proposes and illustrates a conceptual framework for understanding community risk and resilience to wildfires in high-latitude regions. It builds upon the climate adaptation and disaster risk literature and uses the disaster risk reduction cycle to bring together the concepts of risk and resilience. For each stage of the framework, we characterized the factors and dynamics affecting community risk and resilience to wildfires in high-latitude regions. Here, a particular combination of biophysical and social factors that include vegetation types; remoteness; nature-based livelihoods; social, cultural, and health inequalities; limited infrastructure; and rapid environmental and socio-economical changes were observed to determine community risk and resilience to high-latitude wildfires. Previous research demonstrated the influence of each of these factors on community risk and resilience, yet a coherent framework largely remained absent, with most existing studies overlooking either important biophysical or social factors. Our framework integrates these factors in a holistic framework, providing a means to comprehensively think about the biophysical and social factors driving community risk and resilience to high-latitude wildfires.

Moreover, existing research on the human dimensions of high-latitude wildfires remains highly selective about which aspects of the human–climate–fire interaction to include in their assessments, leading to a poor basis for developing policies and management practices [4,27]. This framework addresses this critique by integrating (1) why and how high-latitude communities are at risk of wildfires, (2) the nature of the impacts that wildfires can have on high-latitude communities, (3) the resilience of high-latitude communities to wildfire-related impacts, and (4) the compound drivers and impacts affecting community risk and resilience. We have illustrated how each of these aspects changes over a range of temporal scales (for example, after a wildfire), addressing concerns directed at previous approaches, particularly that they have largely focused on single, static points in time [35]. By integrating these aspects, not only does this framework provide a more holistic approach to identify (non-)climatic factors governing community risk and resilience to high-latitude wildfires over space and time, but its integrated focus on risk and resilience also promotes a more efficient use of resources [30,33,70]. Our framework can, therefore, help practitioners and organizations, such as the Canadian Interagency Forest Fire Centre or the Arctic Council, become aware of what factors have greater influence on community risk and resilience and ensure that their policies are well-grounded ecologically and socially.

Another major advantage of our framework is the consideration of compound drivers and impacts on community risk and resilience. This reflects the fact that wildfire-related events are not the only hazard facing high-latitude communities but are part of broader ongoing climate-driven changes [41]. In our case study, for example, ongoing permafrost thaw was found to negatively affect risk and resilience before, during, and after a wildfire event, either through damages to fire infrastructure and housing or accelerating thaw processes. The consideration of these dynamics has often been neglected in both high-latitude and global social science and humanities research despite being increasingly demanded by both researchers and institutions [176,177]. There are only a few case studies, reviews, and assessment reports globally that highlight the need to consider compound risks in our assessments, yet rarely has this work focused on hazard-specific applications [178]. By considering compound factors in our framework, however, we do not seek to make the high-latitude wildfire challenge even more complex or problematic. Instead, this paper sustains what researchers in other regions globally have identified as building wildfire-adapted communities, which is the imperative need to incorporate and account for the complexity of wildfires, including compounding and cascading risk interactions [4,179,180]. Failing to do so can otherwise bias our future assessments towards a few determinants of risk and resilience and lead to the development and adoption of strategies and policies that

ignore local socio-ecological realities and, therefore, are inadequate to address wildfire risk in high-latitude communities.

Despite these advantages, our framework only offers a conceptual description of the dynamics and factors affecting community risk and resilience to high-latitude wildfires and an illustrative example. There is now a need to empirically test the framework and examine its value. A profitable line of inquiry, where our framework could be particularly useful, would be to examine wildfire risk and resilience in (1) high-latitude urban centers and (2) smaller, more remote settlements in the tundra region. While both of these areas are at increased risk of wildfires [2], they have historically received less scholarly attention compared to rural, Indigenous communities from the boreal region [157,163]. Researchers and practitioners who are interested in these less-studied areas could use our framework here to become aware of the different spatial–temporal characteristics of high-latitude wildfires and ask questions based on them. For example, compound risks have been consistently overlooked in recent wildfire analyses, but with our framework, we encourage researchers and practitioners to think about how these risks can affect wildfire risk and resilience. They will then be able to better capture the conditions that make these areas more (or less) exposed and vulnerable to wildfires and explore opportunities for adaptation. This will ultimately improve our understanding of the human dimensions of high-latitude wildfires and help local, regional, and national governments find suitable wildfire management solutions and strategies for these areas. Although the proposed framework is not explicitly tied to a set of methods, researchers and practitioners can use it with several community-based methodologies, remote sensing tools, or ethnoclimatology modeling [181]. This can involve, for example, documenting how wildfire risks are perceived and managed in different high-latitude communities and using this knowledge to map at-risk areas with fire spread and global vegetation–fire models. Such works can help develop a range of strategies and plans that can then be applied variably across communities, following, for example, the fire adaptation "pathways" concept from Paveglio et al. [182]. As we face the challenges posed by wildfires in high-latitude regions, developing a knowledge base that addresses and recognizes why and how people who live in high-latitude regions are at risk needs to be a priority for the future.

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