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A Nationally Coherent Characterization and Quantification of Mountain Systems in Canada

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Much of Canada is covered by vast and diverse mountains, yet numerous fundamental aspects of Canadian mountain systems have yet to be systematically characterized and quantified in a nationally coherent manner. In response, we delineated mountain areas in Canada according to the Kapos et al definition of mountain areas (K1) and then developed a classification scheme that subdivides K1 into 10 major mountain regions within Canada. Using these boundaries, we conducted numerous geospatial analyses using ArcGIS Pro to advance understanding of the biogeography, people, and economic activities associated with mountains in Canada. By providing consistent and comparable information about mountain systems in the country, our results reveal the national and international importance of Canadian mountain systems across a range of environmental and social metrics. They also provide a foundation for the advancement of research, policy, and work on social issues related to mountains in Canada, all of which have been constrained to date by a lack of nationally coherent analytical frameworks and statistics. We conclude by acknowledging the provisional and culturally situated nature of our work and reflect on the need for more inclusive approaches to designing and interpreting analyses aimed at advancing understanding of mountain systems.

Keywords: *mountains; Canada; GIS; geospatial; mapping; Indigenous Peoples.*

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Introduction

Canada—the second largest country globally—is covered by vast and diverse mountain systems. Illustrative mountain areas include a western cordillera composed of heavily glaciated ranges such as the Canadian Rockies and high peaks such as Mount Logan (5959 masl), an Arctic cordillera in the far north shaped by seasonal extremes of temperature and periods of prolonged light and darkness, and a patchwork of heavily weathered ranges in the east such as the Laurentian and Chic-Choc Mountains (French and Slaymaker 1997). The extent and variety of Canada's mountains have contributed to an outstanding assortment of geological features and ecosystems, as well as the persistence of wide-ranging species such as grizzly bears, caribou, and wolves (Feldhamer et al 2003). Canada's mountain environments have also supported the health and wellbeing of countless generations of people (Berkes et al 2000).

Indigenous Peoples in Canada have inhabited and utilized mountain areas since time immemorial and have developed deep, place-based, and ever-evolving relationships with these areas (RCGS 2018). The arrival of European settlers in the early 1600s and the subsequent process of westward expansion brought new ways of relating to mountains and initiated an ongoing process of colonization that has reshaped the socioecological landscape of Canada's mountain areas (Sandford 2010; Morton 2017). This has included the displacement and disposition of Indigenous Peoples, the growth of settlements and transportation networks, and the establishment of commercial logging, mining, and oil and gas activities (Sandford 2010; Morton 2017). Despite these changes, cultural and linguistic diversity remains high in Canada (Brosseau and Dewing 2018), and the anthropogenic modification of mountain systems appears to be less pervasive than in many other mountainous regions of the world. However, there are still many heavily impacted and fragmented mountain areas within Canada (Palm et al 2020), and climate change is having widespread impacts across mountain systems (Hock et al 2019; Anderson and Radić 2020). Today, Canada has a multicultural society that consists of 38 million people (Statistics Canada 2020), many of whom live in or near mountains or travel to mountain areas for tourism and recreation (Sandford 2010). Given these historical and contemporary relationships, mountains have also become an important aspect of Canadian identity (Sandford 2010); they are prominently featured on currency, official government documents, and materials promoting Canada.

Mountains are an important aspect of Canadian landscapes, history, and identity. However, despite an active mountain research community and some pertinent government programs (eg mountain protected areas and ecological monitoring activities through Parks Canada), numerous fundamental aspects of Canadian mountain systems have yet to be systematically characterized and quantified in a nationally coherent manner. This knowledge

TABLE 1 Research themes and questions.

Research theme	Research question
Mountain biogeography	How much of Canada is covered by mountainous terrain?
	What are the major mountainous regions of Canada?
	What land-cover types are found in Canada's mountain areas?
	To what extent are Canada's protected and conserved areas associated with mountains?
Mountain people	How many people live within and adjacent to mountain areas in Canada?
	Which Indigenous territories intersect with mountain areas in Canada?
	Which Indigenous linguistic areas intersect with mountain areas in Canada?
Mountain economy	What proportion of Canada's gross domestic product originates from economic activity in Canada's mountain areas?
	What are the main economic sectors in Canada's mountain areas?

gap limits the ability to advance research, policy, and social issues related to mountains in Canada and to compare Canada's mountains to other mountainous areas globally.

In response, this study draws on diverse geospatial methods and datasets to advance understanding of the biogeography, people, and economic activities associated with Canadian mountain systems. Our work was guided by several high-level research questions (Table 1), the answers to which informed numerous subsequent analyses, as elaborated in the Results and Discussion section. Our work builds upon past and ongoing mountain research in Canada and aims to provide macroscale insights about several key mountain system variables for Canada, consistent with other international efforts to define and assess mountains systems at large spatial scales (eg EEA 2010). However, we emphasize at the outset that our focus on nationally coherent metrics is meant to complement, not supersede, more localized research findings and ways of knowing mountains, including Indigenous ways of knowing. Furthermore, we stress that our results are based primarily on analytical tools rooted in Western scientific traditions, and, therefore, this work should be understood as providing a partial and culturally situated characterization of Canada's mountain systems.

The analyses reported herein were undertaken in support of the Canadian Mountain Assessment, a flagship initiative of the recently established Canadian Mountain Network (see Kassi et al 2020 for more information about these initiatives).

Methodology

In this study, we used ArcGIS Pro (ESRI n.d.) to examine geospatial data from Canadian and global datasets in relation to the K1 definition of mountains (Kapos et al 2000). The respective data sources, layer names, and spatial resolutions of these datasets are provided in Table 2. Although other definitions for mountain areas exist (Körner et al 2011 [K2]; Sayre et al 2018 [K3]), K1 has been the most widely utilized to date. It was selected to support coherence and comparison between our work and existing mountain-

TABLE 2 Data layers and data sources used in the study.

Research theme	Layer name	Resolution	Data source
Mountain biogeography	K1 Mountain Raster	1 × 1 km	USGS (n.d.)
	2015 Land Cover of Canada	30 × 30 m	Natural Resources Canada (2015)
	Terrestrial Ecozones of Canada	Vector	Agriculture and Agri-Food Canada (2016)
	Canadian Protected and Conserved Areas Database		Environment and Climate Change Canada (n.d.)
Mountain people	2016 Population by Dissemination Block		Statistics Canada (2019a)
	Native-land Territories and Languages		Native Land (n.d.)
	Aboriginal Lands of Canada Legislative Boundaries		Natural Resources Canada (2017)
	Aboriginal Identification Data Table		Statistics Canada (2019b)
	Gridded Population of the World (2020)	~1 × 1 km	CIESIN (2018)
Mountain economy	Gross Domestic Product 2010		World Bank (2012)

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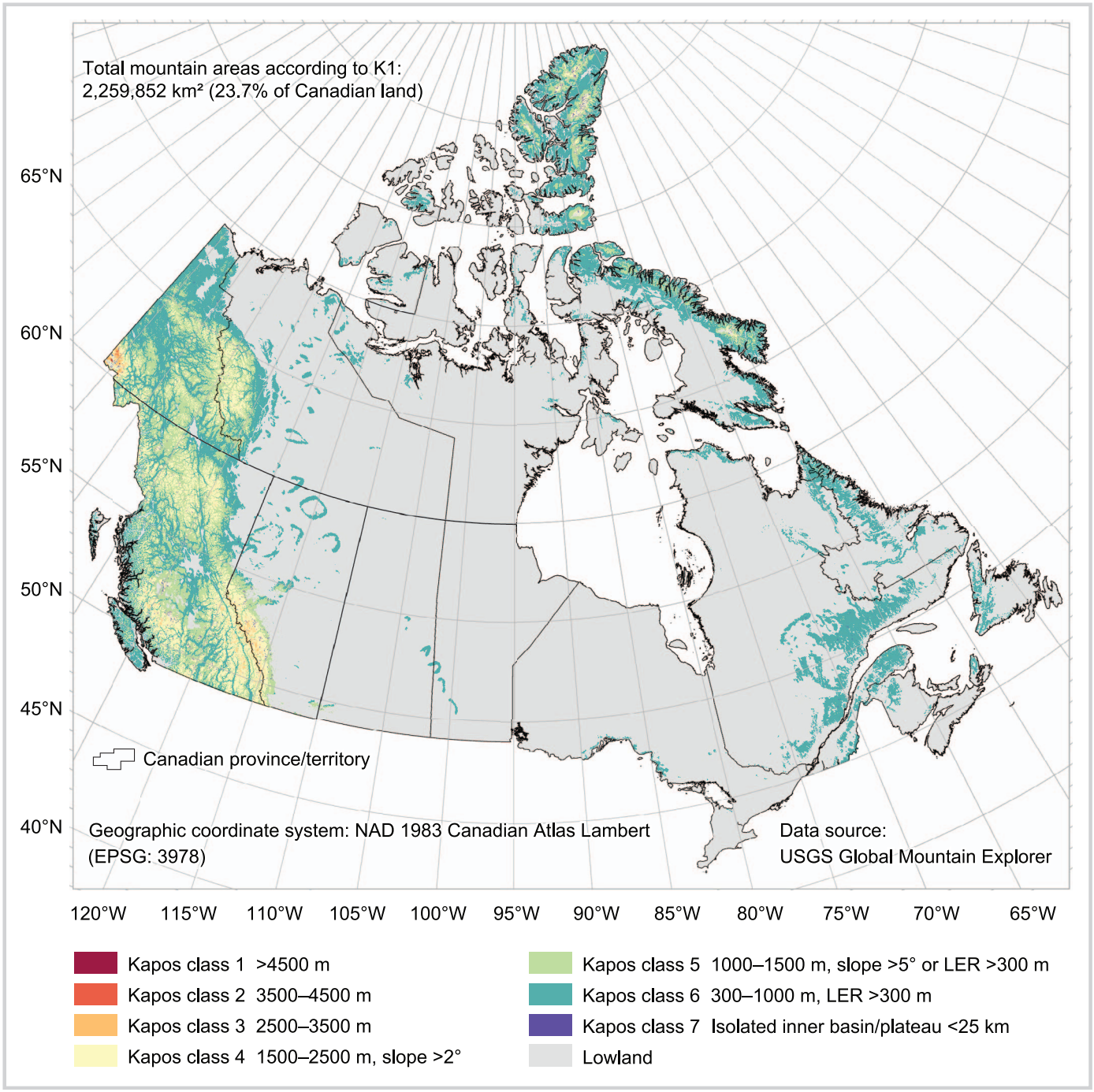
FIGURE 1 Canada's mountainous areas based on the Kapos et al (2000) K1 definition of mountains. Data source: USGS (n.d.). Map by Jiaao Guo



focused assessments. To characterize and quantify the biogeography, populations, and economic activities associated with mountains in Canada, we used basic GIS functions including clipping, geometry calculation of attribute tables, spatial joins, extract-by-mask, and overlay functions, as appropriate. A classification scheme that subdivides K1 into 10 major subregions within Canada was developed in consultation with leading Canadian mountain researchers. Analysis-specific procedures are presented below and fully detailed in Appendix S1 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00071.1.S1). Geospatial analyses were completed between July and November 2020.

Results and discussion

Canadian mountain biogeography

Canada has 2.26 million km^2 of mountainous terrain according to the K1 definition of mountains, an area equivalent to nearly 24% of Canada's total area (Figure 1). These values are based on a spatial intersect of the K1 shapefile and boundary files from the Government of Canada (Statistics Canada 2019a) and will be intercomparable with other analyses based on official government data. To situate these findings in a global context, we calculated the mountain area and percentage coverage for all mountain countries globally. We found that

Canada is close to the global median in terms of percentage of mountainous terrain. However, due to Canada's large size, it ranks fourth globally in terms of absolute mountain area (after China, Russia, and the United States, in that order). The extent of mountainous terrain found in Canada is well illustrated by the following finding: the whole of Switzerland would fit within Canada's mountain area 54 times (USGS n.d.).

We disaggregated the K1 mountain area of Canada into subregions to advance understanding of subnational mountain biogeography and to support cogent subnational analyses. To accomplish this, we divided K1 based on existing "terrestrial ecozones of Canada" boundaries (Agriculture and Agri-Food Canada 2016). Terrestrial ecozones represent areas with broadly consistent biophysical characteristics and were selected as the basis of our framework because they offer well-established and nationally coherent boundaries for large land systems across Canada. Moreover, we wanted to avoid drawing boundaries based on socioeconomic or political criteria, which are inevitably contested. We also value the fact that Canadian terrestrial ecozones are aligned with Omernik's Level II Ecoregion classification system in the United States (EPA 2018), which will enable future transboundary analyses. They also have high concordance with the integrated World Climate Regions and World Landform Regions presented in Sayre et al (2020).

To define spatially explicit major mountain regions in Canada, we identified the terrestrial ecozones that were most closely aligned with the K1 area for Canada. The spatial fit between several terrestrial ecozones and the major mountain areas of Canada is quite good and required minimal or no clipping or extending of ecozone boundaries to match K1 exactly. For the extensive interior of the county where sparse K1 terrain is found, we aggregated the pertinent terrestrial ecozones to come up with western, northern, and eastern interior hills regions, respectively. The K1 terrain within these areas was then clipped out to exclude all non-mountainous terrain found in the larger ecozones. Based on this work, we propose 10 major mountain regions in Canada (Figure 2). The Montane Cordillera (512,366 km^2, 22% of K1), Boreal Cordillera (489,544 km^2, 21% of K1), Arctic Cordillera (378,810 km^2, 16% of K1), and Taiga Cordillera (326,720 km^2, 14% of K1) regions are most extensive. Aside from the "interior hills" regions, we have not changed the existing terrestrial ecozones names ("Interior Hills West" refers to an agglomeration of the Taiga Plains, Boreal Plains, and Prairies ecozones, "Interior Hills Central" to the Boreal Shield and Hudson Plains ecozones, and "Interior Hills North" to the Southern Arctic ecozone). Furthermore, we have not attempted to state the specific mountain ranges that are found within (or that cut across) these boundaries.

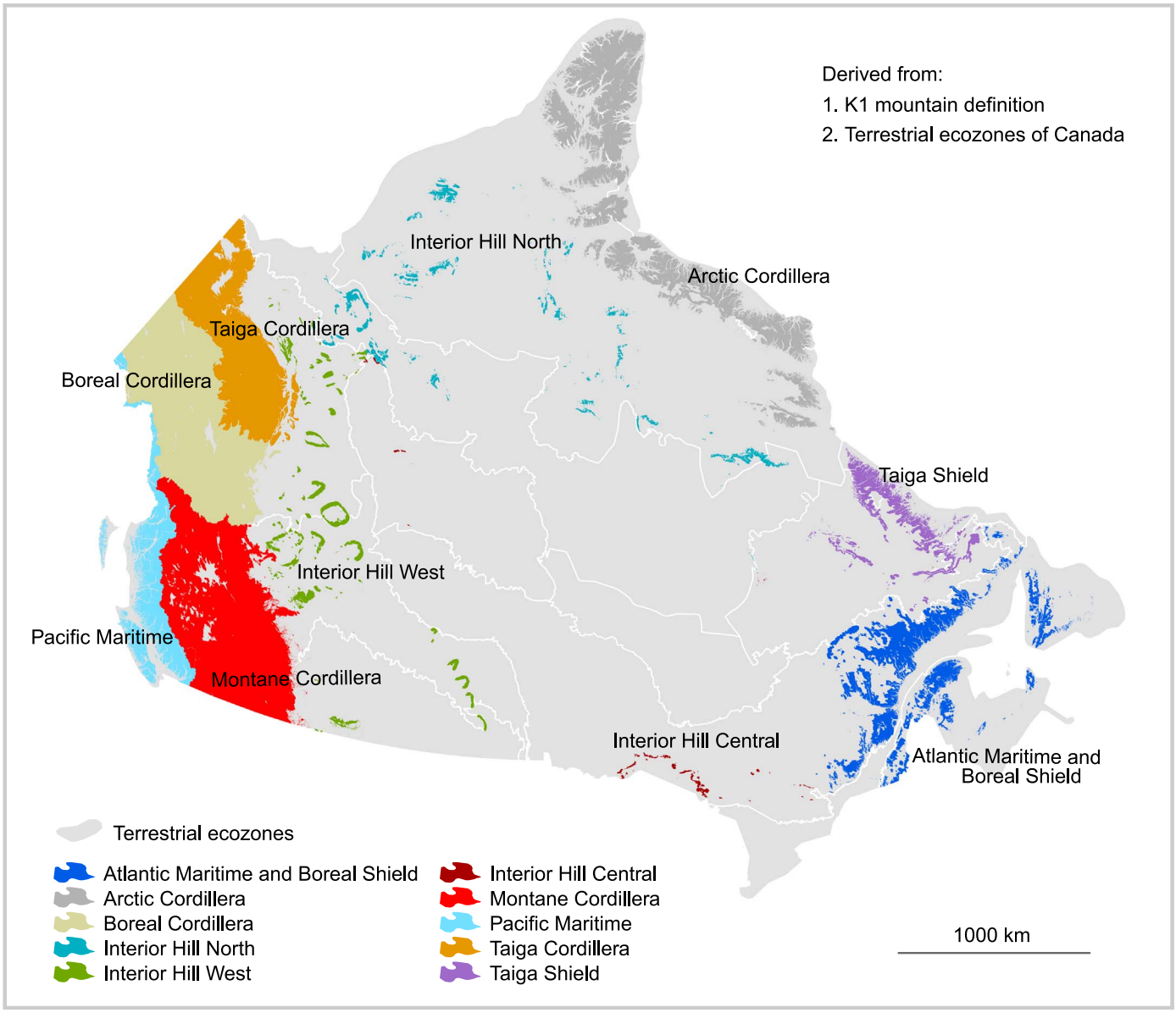
Land cover information is necessary for a large range of applications, including understanding the distribution of wildlife habitat and climate sensitivity as well as environmentally informed planning and permitting processes (Randolph 2011). For our analysis of land cover types found in Canada's mountains, we selected the Government of Canada's 2015 Land Cover of Canada dataset (Natural Resources Canada 2015). This dataset includes nationwide 30 m spatial resolution data for 15 land cover classes. Some land cover from each of these classes is represented in Canada's mountains; however, the most extensive types of land cover are Temperate or subpolar needleleaf forest (781,085 km^2, 36% of K1), Barren lands (362,944 km^2, 17% of K1), Temperate or subpolar shrubland (195,067 km^2, 9% of K1), and Snow and ice (192,266 km^2, 9% of K1). This follows similar patterns of land cover types for mountains reported in the recent global inventory of ecosystems by Sayre et al (2020). However, given the diversity of Canadian mountain systems, the distribution of land cover type at the mountain region scale can differ significantly from nationally aggregated findings.

Globally, protected and conserved areas are often biased toward mountainous regions (Jacobs et al 2021). Our analysis suggests that this pattern is also true for Canada. For example, while around 12% of Canada is covered by terrestrial protected and conserved areas (sum of all forms of land and water protection arrangements), we determined that 19% (436,788 km^2) of K1 mountain terrain in Canada is protected or conserved. These values were calculated by overlaying layers of Canadian Protected and Conserved Areas Database (CPCAD) (Environment and Climate Change Canada n.d.) with Canada's national boundary and K1 mountain areas, respectively. In addition, by comparing CPCAD data with K1 areas specifically, we determined that 36% (436,788 km^2) of Canada's total protected and conserved area and 52% (174,775 km^2) of Canada's National Parks (a specific type of protected and conserved area) are found within mountain systems. These percentages are far in excess of the 24% of Canada's land area found within K1 and illustrate the outsized importance of mountains in Canada as spaces for water source protection, habitat conservation, and tourism and recreation. Furthermore, they suggest that reconciling the legacy of "fortress" conservation, which was used to rationalize the expropriation of Indigenous populations from their ancestral lands (Dowie 2011; Mason 2014), will require particular attention in mountain areas (Figure 3).

Canadian mountain people

Around 1.3 million people live within the K1 area of Canada, representing 3.5% of Canada's total population (Figure 4A). Although the percentage value is relatively small, the actual number of people living in Canada's mountain areas is greater than the entire population of small countries such as Bhutan (World Bank 2019), for example. Most people living in Canada's mountain areas reside within the Montane Cordillera region (78% of the total mountain population), an area that contains the Canadian Rockies as well as vast areas of the mountainous province of British Columbia. Sizable mountain populations are also found in the Atlantic Maritime and Boreal Shield and Pacific Maritime regions (12.7% and 3.6% of the total mountain population, respectively). These values are based on NASA's Gridded Population of the World, Version 4, which provides population counts to 30 arc-second (~1 km) grid cells for 2020 (CIESIN 2018). This publicly accessible gridded population covers most of the K1 area in Canada with consistent resolution, including some remote areas that are not available through the Statistics Canada's census program (Statistics Canada 2019b). We also evaluated the number of people living adjacent to mountains, and we found that 28.9 million people, 78% of Canada's total population, live within 100 km of the K1 boundary (this includes inhabitants of cities such as Vancouver, Calgary, and Montreal, as well as

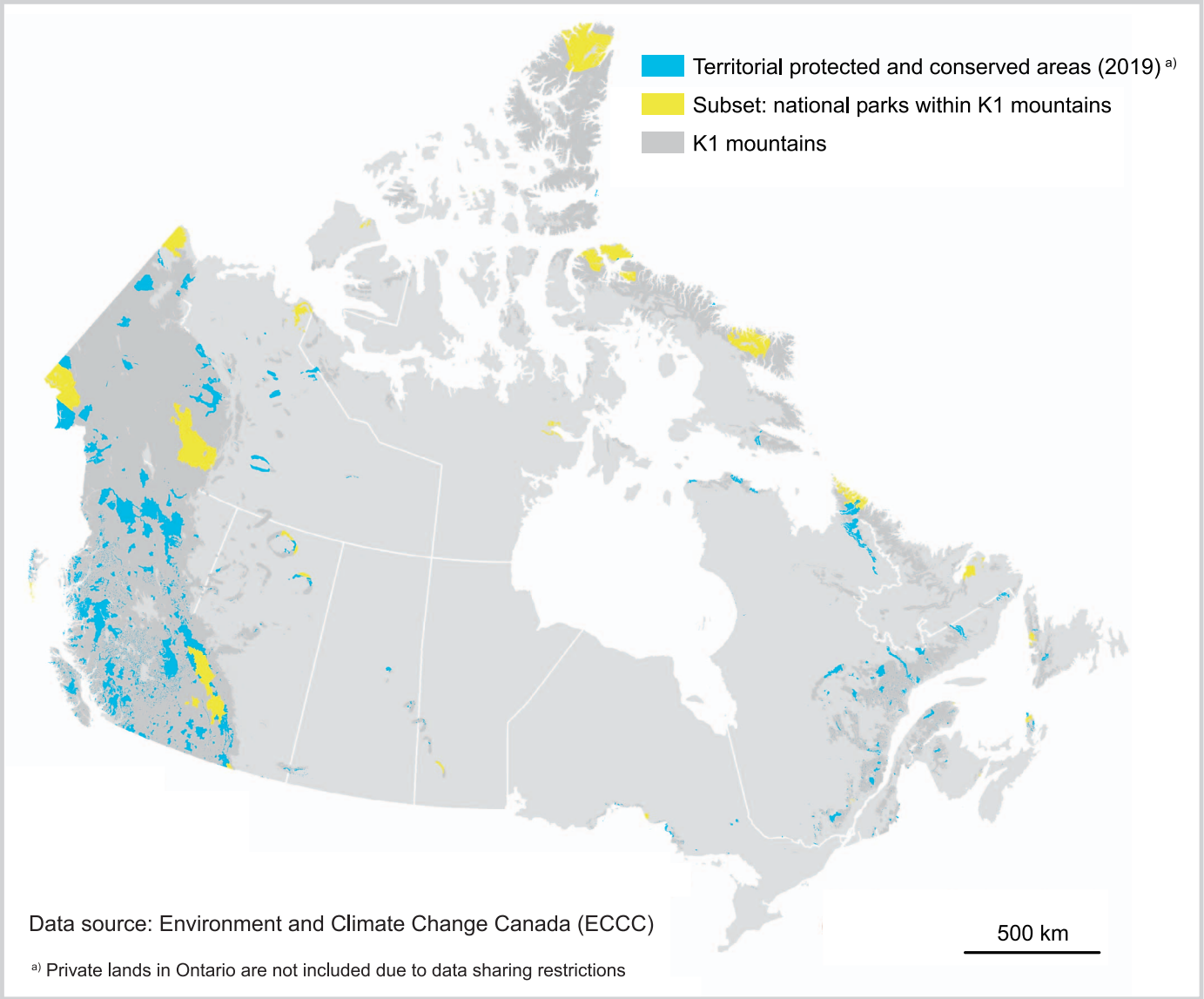
FIGURE 2 Major mountain regions in Canada based on the association of K1 mountain areas and terrestrial ecozones. Data source: Agriculture and Agri-Food Canada (2016). Map by Jiaao Guo



those living in interior regions adjacent to fragmented and sparsely distributed K1 terrain such as the Greater Toronto Area). Our 100 km distance threshold is based on reasonable access to, and probable use of, mountains and their associated services and is consistent with the widely accepted 100 km threshold used to evaluate populations living in proximity to coastal environments (MEA 2005). Combining our population analysis, we see that almost 82% (30.2 million people) of Canada's total population live within or adjacent to mountain areas, a finding that reinforces the idea that mountains are a particularly salient aspect of Canada's sociocultural fabric.

We also attempted to determine the number of Indigenous Peoples residing in Canada's mountain areas (Figure 4B). The best available data for this analysis are Aboriginal Identity at the census subdivision (CSD) level (Statistics Canada 2019b). Using these data, we found that 6% of those living in mountain areas self-identify as First Nations, Métis, or Inuit, a value that is only 1 percentage point higher than the national average. However, 108 of 572 CSDs (19%) with mountainous terrain have >80% Indigenous population. Thus, although the total percentage of Indigenous Peoples in mountain areas is not especially high, there are many mountain areas where Indigenous populations are very high on a per capita basis. We found that most Indigenous Peoples in mountain areas identify as First Nations (~187,000 people), followed by Métis (~125,000 people) and Inuit (~10,000 people). However, these values are based on population numbers for whole CSDs. We caution that this methodology somewhat overestimates the number of people actually living within K1, as some CSDs contain both K1 and non-K1 areas. At the same time, we acknowledge that our analysis does not sufficiently account for the significant number of Indigenous Peoples across Canada who live outside of K1 areas but maintain deep cultural connections to mountain places.

FIGURE 3 Protected and conserved areas within K1 mountain areas. Data source: Environment and Climate Change Canada (n.d.). Map by Jiaao Guo



Understanding the extent and distribution of Indigenous territories is essential for elevating appreciation of the scope and diversity of mountain system uses and knowledge among Indigenous Peoples in Canada. Utilizing data provided by Native-Land.ca (Native Land n.d.)—a nondefinitive but relatively comprehensive collection of Indigenous territories and linguistic areas—we conducted a spatial intersect and clipping exercise to determine which Indigenous territories overlap with K1. Our results suggest that the territories of at least 150 Indigenous groups intersect with K1 (Figure 5). One third of these territories have at least 80% of their total area within K1; the territories with the greatest amount of land in mountainous areas are found in the western portion of Canada. Another way of understanding Indigenous presence in Canada's mountains is the distribution of Indigenous linguistic areas. Using similar data and methods, we found that at least 92 linguistic areas overlap with the K1 area in Canada, 20 of which have at least 80% of their total area within K1 (Figure 6). We recognize that polygons of territories are imperfect, incomplete, and static representations that do not fully represent the relationships, rights, and responsibilities that Indigenous Peoples have to these places. Nevertheless, these analyses shed light on the historical and present distribution of Indigenous Peoples in the mountains of Canada, reinforcing claims of Aboriginal title in mountain areas (Foster et al 2011), and affirming the importance of Indigenous knowledges in understanding mountain systems.

Canadian mountain economies

We examined the contribution of economic activities within K1 to total gross domestic product (GDP) to determine the national-scale importance of Canada's mountain economies. We used gridded World Bank GDP data for 2010 (World Bank 2012), as these data had the best fit with K1. To arrive at contemporary values for GDP, we assumed that regional GDP growth is consistent across the country and was linear between 2010 and 2019 (we excluded consideration of 2020 GDP due to the distorting effects of COVID-19). These assumptions are consistent with observed patterns of GDP

FIGURE 4 (A) Total population within K1; (B) self-identified Indigenous population (First Nation, Métis, or Inuit) within K1. The latter includes only census subdivisions (CSDs) that have at least 50% of their area within the K1 mountain boundary and a minimum of 500 Indigenous inhabitants. Data sources: CIESIN (2018) and Statistics Canada (2019b). Map by Jiaao Guo

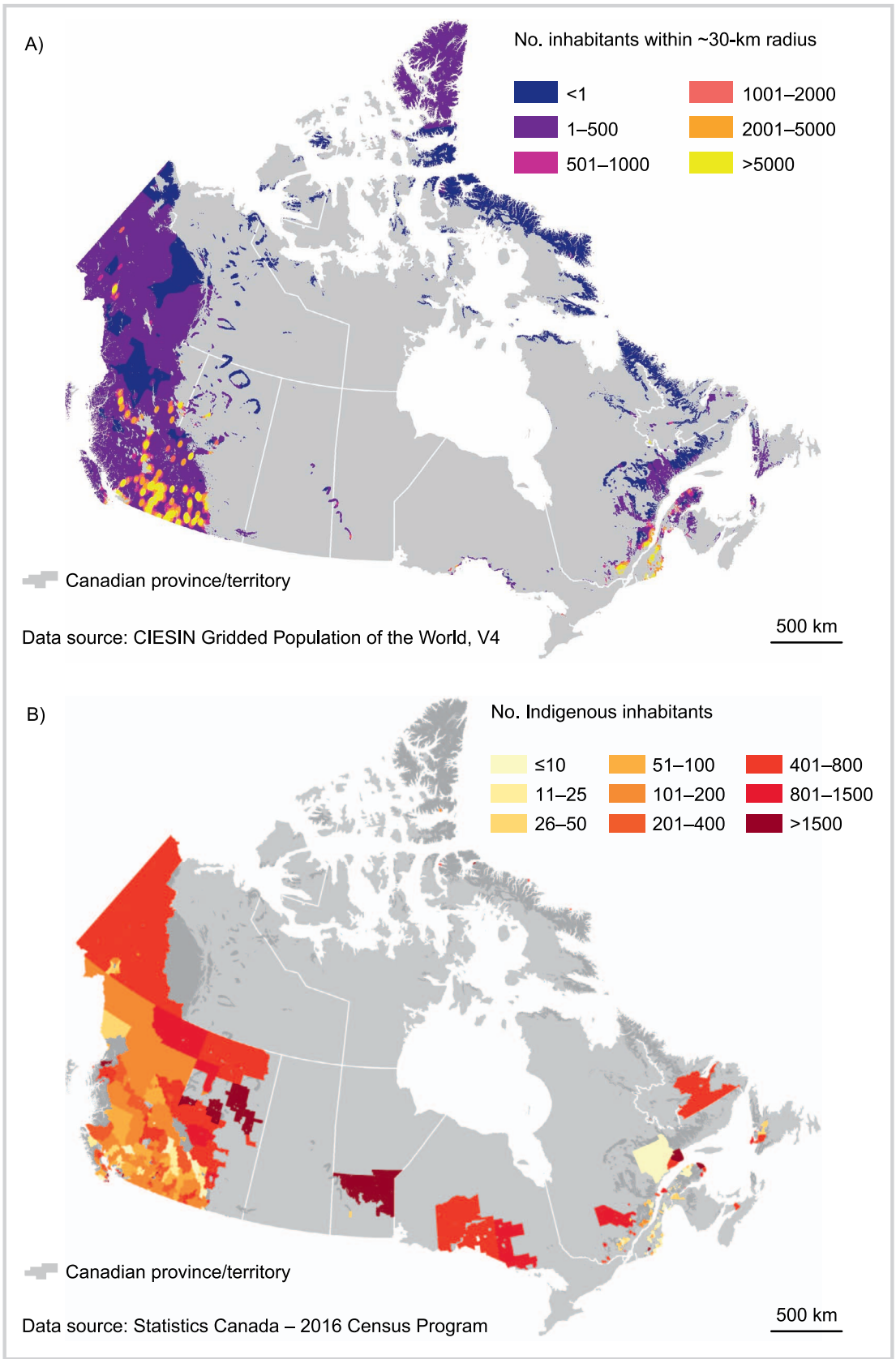


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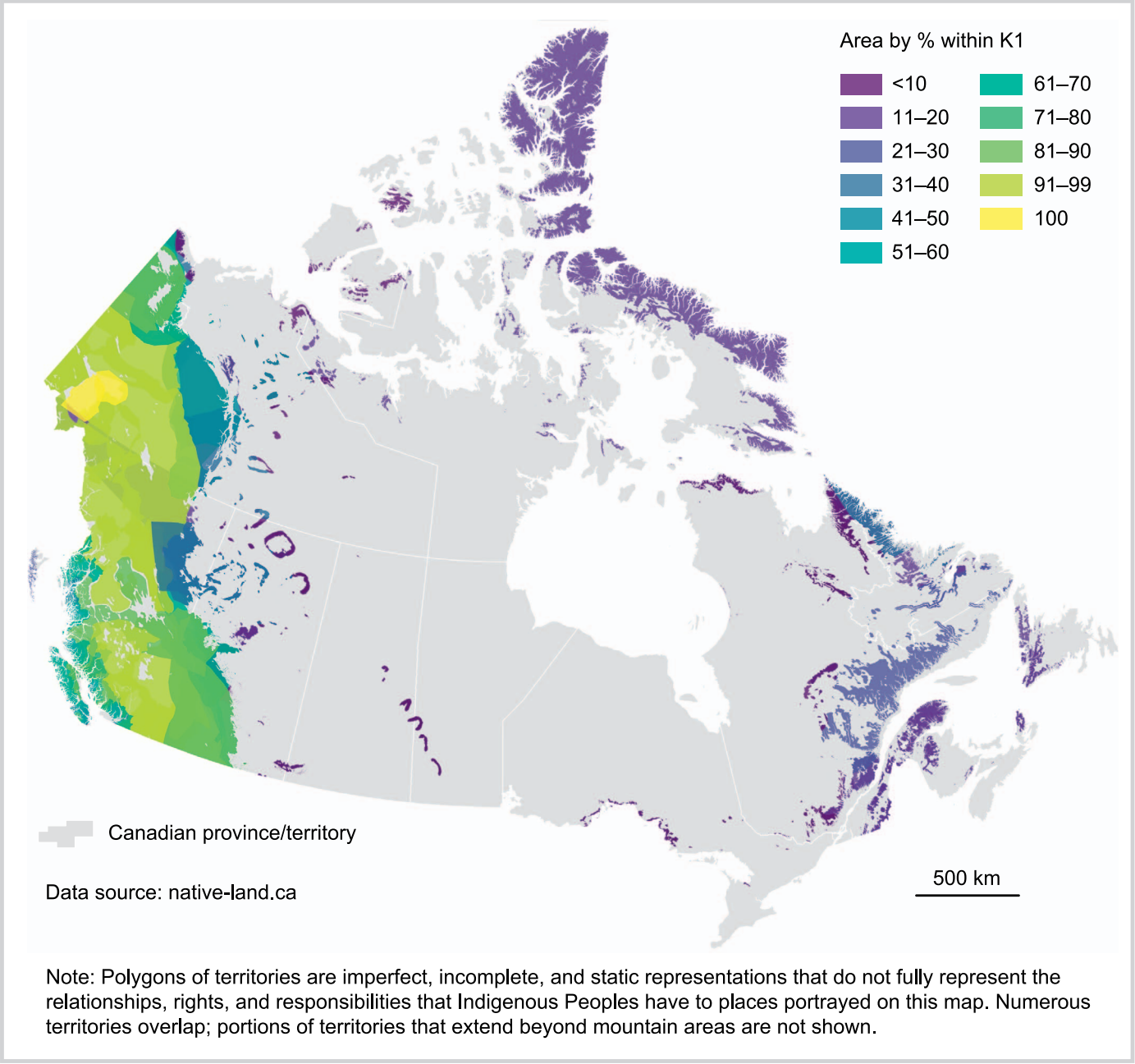
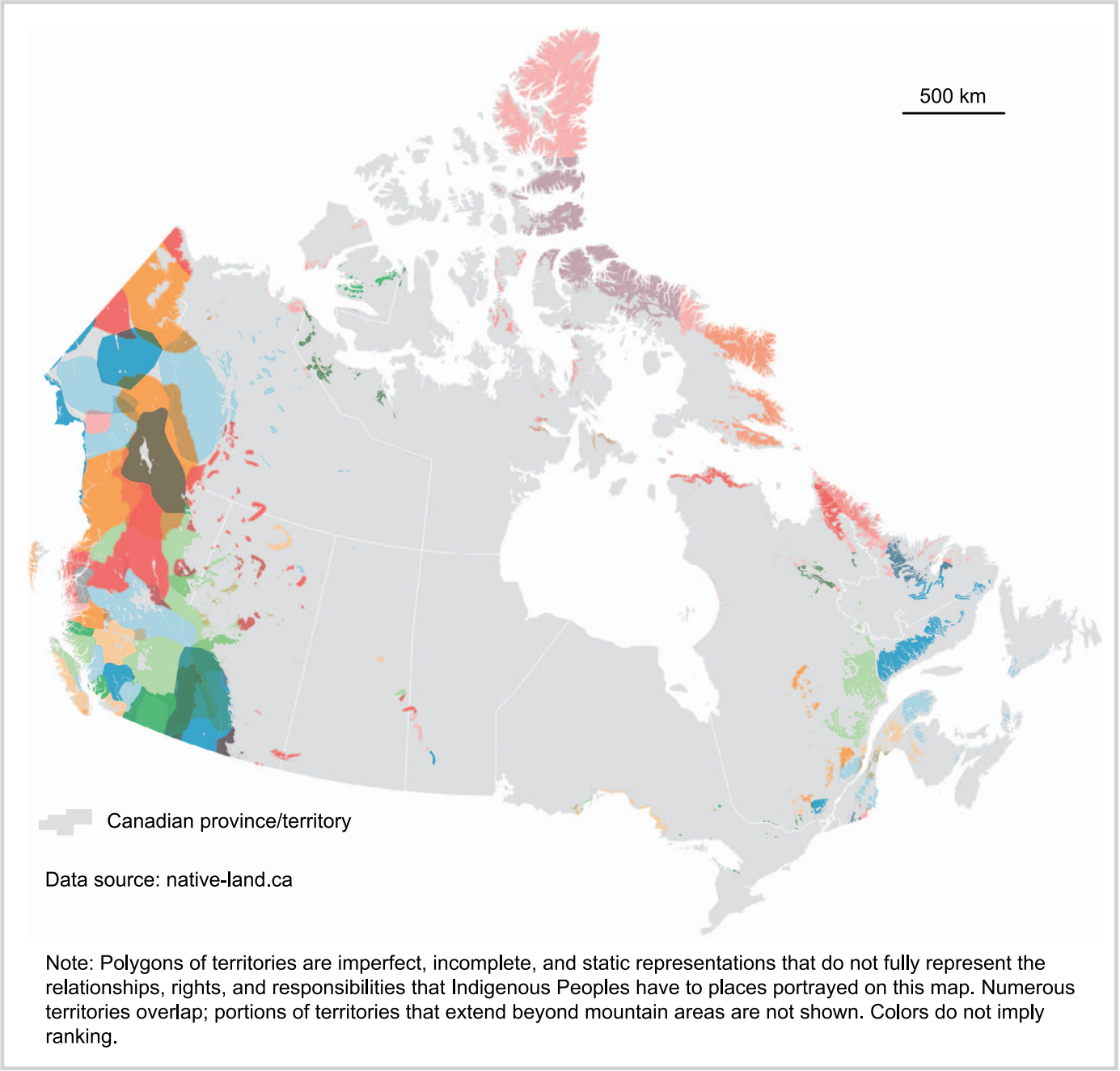
FIGURE 5 Indigenous territories associated with K1 mountain areas. A version of this map with territories labeled and named is available in Appendix S2 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00071.1.S1). Data source: Native Land (n.d.). Map by Jiaao Guo



growth in Canada for this period (IMF n.d.). We then applied a linear transformation to the 2010 data to arrive at the 2019 GDP associated with economic activity within K1. We found that mountain economies contribute 3.75% of Canada's total GDP, while approximately 75% of Canada's GDP is generated by economic activity within 100 km of the K1 boundary. These values mirror population numbers and suggest that economic output is proportional to population; Canada's mountain economies are therefore no more or less productive than economies located in other types of environmental systems. However, because many economic activities associated with mountains are not found in, or substitutable with, economic activities in lowland areas (eg mountain guiding, ski areas), the sociocultural importance of mountain-specific economic activities is certainly greater than our GDP-focused analysis suggests. Furthermore, the value of subsistence-based activities and mountain-sourced ecosystem services is not considered here (although aspects of the value of ecosystem services are reflected indirectly in GDP) (Klein et al 2019; Schirpke et al 2019).

Canada's mountain economies comprise various sectors but lean heavily toward tourism (eg skiing, parks visitation) and natural resource-related activities (eg forestry, mining) (Sandford 2010). We attempted to quantify the breakdown of economic activity by sector for K1 and major mountain regions, respectively, but were unable to identify suitable, nationally coherent data. At present, provincial and municipal government sources are the best option for details

FIGURE 6 Indigenous linguistic regions associated with K1 mountain areas. A version of this map with linguistic regions labeled and named is available in Appendix S3 (*Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00071.1.S1). Data source: Native Land (n.d.). Map by Jiaao Guo



about economic activities within mountain areas. These resources could be comprehensively collated and evaluated in the future to quantify economic activity by sector, but such an effort was beyond the scope of this study.

Limitations

This study represents an initial attempt to characterize and quantify Canada's mountain systems in a nationally coherent manner. Although the methods employed are well established, our combination of specific datasets and other analytical choices were largely original. While such choices were guided by our respective expertise and input from other Canadian mountain researchers, different potentially valid analytical choices might have yielded slightly (or substantially) different results. For example, our use of the K1 definition of mountains is consistent with much work globally, but K1 has been criticized, inter alia, for underestimating mountainous terrain in rugged lowlands (Körner et al 2017; Sayre et al 2018). This is an important limitation given Canada's notably long and mountainous coastlines; our statistics do not thoroughly address coastal mountain systems that might be recognized in other mountain definitions (eg coastal margins of British Columbia are classified as mountainous with K3 but not with K1) (see Appendix S4, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-20-00071.1.S1). Data availability issues

also constrained our efforts. For example, the finest enumeration level for census data in northern Canada is not sufficient to isolate mountain-specific populations. A similar situation applies to economic data. In response, we used gridded population and GDP data based on models from NASA's Gridded Population of the World and the World Bank, but such data may not match actual figures from community or municipal offices. More fundamentally, although we endeavored to conduct analyses that were cognizant of, deferential to, and of relevance for Indigenous Peoples in Canada, we did not engage with Indigenous individuals when designing our analyses or interpreting our results. Our work is rooted in Western scientific methods and conceptions of mountains and consequently might not resonate with those outside of our own epistemic community. For such reasons, our work should be understood as both provisional and culturally situated.

Conclusions

Mountains are an important aspect of Canadian landscapes, history, and identity. However, the lack of consistent and comparable information about mountain systems has been a barrier to advancing research, policy, and social issues related to mountains in Canada. It has also limited our ability to situate Canada's mountains in a broader global context. In response, this study drew on diverse geospatial methods and datasets to provide fundamental insights about the biogeography, people, and economic activities associated with Canadian mountain systems.

Key findings from this work include the following:

- Canada is the fourth most mountainous country by area globally; its mountainous terrain could contain the whole of Switzerland 54 times.
- Canada's mountains contain a remarkable diversity of land cover types as well as a disproportionate percentage of the country's protected and conserved areas.
- Almost 82% of Canada's total population lives within or adjacent to mountain areas, reinforcing the idea that mountains are a salient aspect of the sociocultural fabric of Canada.
- Many Indigenous territories and linguistic regions are associated with mountain areas, highlighting diverse, place-based, and long-standing relationships of Indigenous Peoples with mountain systems in Canada.
- The contributions of economic activities in Canada's mountain areas to GDP are comparable to contributions from economic activities in non-mountainous areas. However, this does not take into account the value of subsistence-focused pursuits, mountain-sourced ecosystem services, or the richness of many economic activities that are unique to mountain regions.

In addition to these and other nationally coherent findings, we developed a classification scheme that subdivides K1 into 10 major mountain regions within Canada. This classification scheme supported our systematic subnational analyses and can be used for similar purposes in the future.

It is our hope that this initial characterization and quantification of Canadian mountain systems will increase appreciation for Canada's diverse and expansive mountain systems, both within Canada and among our colleagues in the international mountain research and development community. Further, we believe that numerous strands of inquiry can benefit from and build upon this work, and we look forward to seeing how our nationally coherent findings might support the advancement of work related to mountains in Canada. However, we caution that our efforts should be understood as provisional and culturally situated. We tender our results with deep appreciation of these caveats and recognize the need for a participatory approach to refining and extending the work reported herein, including through meaningful engagement with Indigenous knowledge holders.

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Supplemental material

APPENDIX S1 Elaboration of analysis methods (in ArcGIS) for each research question.
APPENDIX S2 Figure 5 with labels and annotations.
APPENDIX S3 Figure 6 with labels and annotations.
APPENDIX S4 Differences in mountain areas according to K1 versus K3.

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