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Unpacking the WEF Nexus Index: A Regional and Sub-Regional Analysis of Northern Canada

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Abstract: The water–energy–food (WEF) nexus has emerged as a leading tool for assessing integrated resource management strategies and for monitoring progress towards the WEF-related Sustainable Development Goals. A notable outcome of WEF nexus research has been the calculation of the global WEF Nexus Index, which provides a quantitative ranking of country-level WEF security for 170 nations. As valuable as this ranking is, the aggregation of country-level WEF data obscures regional differences, particularly in remote regions that are sparsely populated and differ in geography, economy, and climate. This has proven to be the case for northern Canada, which despite representing 40% of Canada’s total land area, accounts for less than 1% of the Canadian population, most of whom are Indigenous. Whereas Canada ranks 5th globally in their WEF security, northern Canada, if treated independently, would rank 67th on the global WEF Nexus Index rankings. Evaluating each WEF sector independently, northern Canada would rank 22nd in water security, 90th in energy security, and 113th in food security. Our results further reveal that considerable inter-regional variability exists between northern territories and provinces, where Nunavik would rank 54th, Northwest Territories 67th, Yukon 69th, Labrador 80th, and Nunavut 107th on the global index. By highlighting these differences, we hope that this research can aid decision-makers in developing informed, regionally specific, and integrative resource policy responses that remedy rather than amplify existing WEF-related inequalities.

Keywords: WEF nexus; northern Canada; arctic; Sustainable Development Goals; water security; energy security; food security

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1. Introduction

Over the past decade, the water–energy–food (WEF) nexus has emerged as a leading tool for assessing integrated resource management strategies and for monitoring progress towards the WEF-related Sustainable Development Goals (SDGs 2, 6, and 7). The WEF nexus is a method of examining and evaluating WEF resources as a holistic, interconnected system rather than three independent, disjointed sectors. A considerable body of scholarship now exists on the WEF nexus [1–6], which has lent important insight into the inherent linkages and interdependencies that exist between WEF systems [7,8]. Between 2008–2019 alone, 396 papers were published on the WEF nexus, many of which highlight the need for the multicentric treatment of WEF systems [9]. A notable outcome of WEF nexus research has been the calculation of the Global WEF Nexus Index. The WEF Nexus Index integrates data from 21 selected indicators to determine a quantitative ranking of country-level WEF security. These rankings, which include 170 nations, are used to assess national-level progress toward achieving the WEF-related SDGs [10,11].

As valuable as these national rankings are, it was acknowledged by Simpson et al. [10] that these scores should not be considered end points, but rather points of entry for understanding regional and sub-regional variability in WEF security conditions. At national levels, the aggregation of WEF data obscures regional differences, particularly in remote regions that are sparsely populated and that differ in geography, economy, and climate. These variabilities may be especially prominent in remote regions that are populated by Indigenous peoples [6]. However, by disaggregating national WEF indicator data, regional and sub-regional differences can be discerned, which can enable decision-makers to systematically integrate policy preferences based on an informed understanding of regional conditions.

In this research, we set out to disaggregate data for northern Canada—an area represented by Yukon, Northwest Territories, Nunavut, Nunavik, and Labrador—from Canada's national WEF Nexus Index. Whereas Canada is ranked 5th globally in terms of WEF security [11], northern Canada has been characterized by high rates of WEF insecurity, including limited access to clean water, an overdependence on non-renewable energy sources, and having the highest rates of Indigenous food insecurity among all industrialized nations [6]. Our aim in this study was to assess the differences that exist between northern and southern Canada and highlight how national-level data can obscure the resource insecurities that are experienced in more remote and Indigenous-populated regions. Highlighting these differences can then inform more effective policy responses that are capable of achieving inter-regional equity in WEF security while also providing a more accurate account of Canada's national progress towards achieving the Sustainable Development Goals.

The following section provides a background on the development and calculation of the WEF Nexus Index and summarizes Canada's global WEF Nexus Index rankings. Section 3 describes our study area of northern Canada and outlines our methods of data collection and analysis. Section 4 contains the results of our analysis, and in Section 5, we discuss our findings, including the factors driving regional and intra-regional WEF disparities. This section includes a discussion on the suitability of applying country-level indicators to regional scales and the need for other regionally specific indicators to discern the interactions between WEF systems.

2. Background

The WEF Nexus Index is a quantitative measure and representation of country-level WEF security based on 21 water, energy, and food security indicators. These 21 indicators were determined following a global assessment of water, energy, and food-related databases and were selected based on relevance, data availability, and reliability [11]. Among the 21 indicators that were selected, 7 are used to measure water security, 6 represent energy security, and 8 are used to assess food security (Table 1).

The WEF Nexus Index was developed in accordance with the Joint Research Centre's Competence Centre on Composite Indicators and Scoreboards (JRC:COIN) [12]. The analytical framework for the WEF Nexus Index consists of three equally weighted sub-indexes, or "pillars", each one representing a WEF sector. The equal weighting of each pillar reflects the multicentric nature of the WEF nexus by ensuring that each resource sector has equal importance in the calculation of the overall index [10]. Within each WEF pillar are two equally weighted sub-pillars representing access and availability. The access sub-pillar refers to equitable access to and distribution of WEF resources, whereas the availability sub-pillar relates to the physical availability of the resource itself [11]. Each sub-pillar then contains a subset of indicators representing access to or availability of its corresponding WEF resource (Table 1).

To calculate WEF Nexus Index values, the indicator data were first normalized using the min–max method. Following this method, the country i 's normalized value for indicator j would be calculated as

$$x_{ij}^{norm} = \frac{x_{ij}^{obs} - x_j^{min}}{x_j^{max} - x_j^{min}} \times 100 \quad (1)$$

where the superscript *obs* indicates the observed value for country *i* and the superscripts *max* and *min* denote the maximum and minimum values of indicator *j* among the sample. This procedure converts data to a uniform, unitless scale from 0–100 so that it may be aggregated across indicators [13]. Each sub-pillar (*SP*) is then calculated as the weighted arithmetic average of its normalized indicator values,

$$SP_i = w_j x_{ij}^{norm} + \dots + w_n x_{in}^{norm}, \quad (2)$$

where w_j is the assigned weight of indicator *j*, *n* is the number of indicators within the sub-pillar, and the sum of w_j through w_n for each sub-pillar is one. The WEF pillar scores are then calculated as the arithmetic average of their underlying access and availability sub-pillars. For example, the water pillar (*WP*) for country *i* would be calculated as

$$WP_i = \frac{SP_{Access,i} + SP_{Availability,i}}{2} \quad (3)$$

Table 1. Indicators used in the WEF Nexus Index [11].

Water Indicators	Energy Indicators	Food Indicators
Water Access	Energy Access	Food Access
1. Percentage of people using at least basic drinking water services.	8. Access to electricity (% of population).	14. Prevalence of undernourishment (%).
2. Percentage of people using at least basic sanitation services.	9. Renewable energy consumption (% of total energy consumption).	15. Percentage of children under 5 affected by wasting.
3. Degree of integrated water resource management implementation.	10. Renewable electricity outputs (% of electricity output).	16. Percentage of children under 5 who are stunted.
	11. CO ₂ emission per capita.	17. Prevalence of obesity in the adult population (18 and older).
Water Availability	Energy Availability	Food Availability
4. Annual freshwater withdrawals.	12. Electric power consumption (kWh per capita).	18. Average protein supply (gr/caput/day).
5. Renewable internal freshwater resource per capita.	13. Energy imports (net % of energy use).	19. Cereal yield (kg/ha).
6. Environmental flow requirements.		20. Average dietary energy supply adequacy.
7. Average precipitation (mm/yr.).		21. Average value of food production (\$/capita).

The WEF Nexus Index (*WNI*) for the country *i* can then be calculated as the arithmetic average of its water pillar, energy pillar (*EP*), and food pillar (*FP*) scores:

$$WNI_i = \frac{WP + EP + FP}{3} \quad (4)$$

Based on these calculations, the WEF Nexus Index for Canada is 75.51 (out of 100), making it the fifth most WEF-secure country (*N* = 170) [11]. Canada's water pillar value was calculated to be 68.50, which ranks 42nd globally. Canada scores high for providing basic access to drinking water and safely managed sanitation services but had a relatively low score for average annual precipitation. Canada's energy pillar value was 84.81, which ranked it as being the 3rd most secure. Canada's high energy score is attributed to the universal access to electricity and being a net exporter rather than importer of energy. However, Canada's energy score is negatively influenced by relatively low renewable energy consumption and higher than average CO₂ emissions. Last, Canada's food pillar was calculated to be 73.22, ranking it 13th worldwide. This score is attributed in part to

Canada having a low prevalence of undernourishment and children less than five years of age who are affected by wasting or stunting. However, this value is offset by high rates of obesity in the adult population.

The WEF Nexus Index serves as a useful mechanism for policymakers to assess how well their respective countries are meeting WEF security benchmarks, which WEF sectors are more or less secure, and how their scores compare to others, either globally or in their respective regions. Table 2 shows the WEF Index and resource pillar scores for the top five ranked nations.

Table 2. Top five ranked nations in the WEF Nexus Index [11].

Country	Global Ranking	Index Score	Water	Energy	Food
Norway	1st	80.9	79.1	93	70.5
New Zealand	2nd	77.3	79.1	74.6	78.2
Sweden	3rd	76.9	78.2	82.3	70.1
Iceland	4th	76.6	79.4	93.2	57.2
Canada	5th	75.5	68.5	84.8	73.2

3. Methods

3.1. Study Area

Our study area of northern Canada includes Yukon, Northwest Territories, Nunavut, Nunavik, and Labrador (Figure 1). In the case of Nunavik and Labrador, these two regions represent the northern extensions of the provinces of Quebec and Newfoundland and Labrador. Geographically, northern Canada encompasses over 4 million km², or roughly 40% of Canada's total land area. Although Canada's northern region is vast, less than one percent of Canada's total population lives there (estimated 200,418 out of roughly 38 million) [14]. Northern Canada's population is dispersed across 111 communities, the largest being Yukon's capital city of Whitehorse (population 28,085). Among the estimated 200,418 people who live in northern Canada, roughly 50% (100,650) self-identify as Indigenous [15]. However, in Nunavut and Nunavik, Inuit represent as much as 90% of the population.

3.2. Data

Data collection followed a systematic data search of the 21 WEF Nexus Index indicators for northern Canada. We began by searching federal government data sources, including Statistics Canada, Agriculture and Agri-Food Canada, and Natural Resources Canada, followed by provincial and territorial government databases. If government databases did not yield the necessary data, non-government data repositories were utilized, such as Canada's Federated Research Data Repository and the Ontario Data Documentation, Extraction Service, and Infrastructure (ODESI) database. ODESI is a web-based digital repository for social science data that are housed in micro and aggregated form. Next, we examined peer-reviewed publications, research reports, and other grey literature sources. When these sources still did not yield the necessary indicator data, we examined alternative sources and methods for calculating indicator data. Altogether, our search yielded data points for 77 out of the 105 (73%) indicator values between the five northern Canada regions.

In some cases, our data search failed to identify the exact corresponding indicators that were used in the WEF Nexus Index. Due to the absence of corresponding data, we then identified and selected alternative measurements that could serve as proxies for indicators with missing data. For example, no direct data could be found for indicator 21, average value of food production, for any of the regions. As an alternative, we derived indicator values from Supply and Use Tables (SUTs). SUTs provide data on all of the economic activity taking place in Canadian provinces and territories and include detailed breakdowns of different industries, including agricultural-related activities, allowing us to calculate the average value of food production in each region. In the cases of Nunavik

and Labrador, data on gross farm receipts at the sub-provincial levels were also used to disaggregate regional data from their provincial totals. We tested the validity of our method by calculating the average value of food production for all of Canada using the SUTs and comparing it to Canada's indicator value in the WEF Nexus Index and determined that it provided a robust calculation of the food production value. This form of substitution is considered to be an appropriate and acceptable practice when calculating composite indicators [12]. A total of 19 alternative indicator values (18%) were used in place of the original indicators across the five northern Canada sub-regions, all of which were tested for robustness following the above method.

Figure 1. Northern Canada study area. Note: YT: Yukon, NT: Northwest Territories, NU: Nunavut; BC: British Columbia; AB: Alberta, SK: Saskatchewan, MB: Manitoba, QC: Quebec, NB: New Brunswick, NS: Nova Scotia, PE: Prince Edward Island, NL: Newfoundland and Labrador.

If no precise data or usable proxy indicator data could be found, then the indicator was excluded entirely. Missing data are allowable in the calculation of composite indicators, although it is recommended to have data for at least 65% of the indicators for each region for the validation of the index [12]. This threshold was met for all five regions, as data were found for at least 19 of the 21 indicators (90.5%) in each region. A total of nine indicator values (9%) were excluded from our analysis.

3.3. Analysis

After collecting all of the available indicator data, the data were then aggregated across the five sub-regions to calculate the indicator values for northern Canada as a whole. This allowed us to make regional comparisons between northern and southern Canada as well as sub-regional comparisons between the northern territories and provinces.

Data analysis was conducted using the COIN Tool, the same program that was used to calculate the WEF Nexus Index [10]. The COIN Tool is an open access Excel-based tool that was developed by JRC:COIN that automatically normalizes, treats, and aggregates indicator data to calculate composite indicators and to provide rankings based on the calculated scores of the sample [16]. We utilized the same data analysis framework as the WEF Nexus Index, including the data normalization and aggregation methods outlined in Equations (1) through (4). We also followed the WEF Nexus Index's data treatment procedures. For example, significant outliers in the dataset were treated following

JRC:COIN guidelines, as they can influence important descriptive statistics and cause the data set to be misinterpreted when the min–max normalization method is used [12]. If an indicator's skewness and kurtosis values were both greater than the thresholds of 2.0 and 3.5, respectively, then the COIN Tool automatically treated the indicator for outliers by a process of Winsorisation or Box-cox transformation. In our analysis, four indicators were treated by Winsorisation, and two indicators were treated by Box-cox transformation. Data values for two variables were also manually adjusted to reduce the absolute values of skewness and kurtosis and to better fit the conceptual framing for these indicators. The maximum value for indicator four, annual freshwater withdrawals as a percentage of internal resources, was truncated at 100%, and the minimum value of indicator 13, net energy imports as a percentage of energy use, was truncated at 0% to exclude the negative values that indicate net exporters of energy [10].

Data for northern Canada and the five northern Canada sub-regions were entered into the COIN Tool along with country-level data provided by the WEF Nexus Index in order to populate the dataset. The inclusion of northern Canada and the five northern Canada sub-regions resulted in a total of 176 countries/regions in the total dataset. Weights were then assigned to the indicators equal to those used in the original WEF Nexus Index, after which the normalized indicator values and the sub-pillar, pillar, and overall WEF Nexus Index scores were calculated. In cases where there were no data for an indicator, the COIN Tool calculated the sub-pillar score by only taking the weighted mean over the indicators with the data [16]. After calculating the index scores, we determined where northern Canada would rank in the global dataset if it were treated independently and compared northern Canada's rankings with Canada's country-level rankings. We also compared the five northern sub-regions using the same procedure.

4. Results

4.1. Northern Canada Regional Results

As noted above, Canada is ranked 5th on the Global WEF Security Index, with a composite score of 75.51. Our calculations for northern Canada arrived at a WEF security Index score of 57.50, ranking northern Canada 67th if treated independently (Table 3). Northern Canada would therefore rank 62 spots behind Canada in the global WEF Nexus Index rankings, indicating a substantial difference in WEF security. Northern Canada's WEF Nexus Index ranking places it in the company of Thailand (ranked 66th) and Belarus (ranked 68th) in the world rankings of WEF security.

Northern Canada's water pillar score was calculated to be 72.42, ranking it 22nd globally. This indicates that access to and the availability of water resources in northern Canada are relatively secure. Northern Canada's water security score was positively influenced by the amount of renewable internal freshwater resources per capita and limited annual freshwater withdrawals. However, northern Canada's percentage of people with access to basic drinking water services was roughly 12.5 percentage points less than Canada's country-level data. These findings illustrate the increased difficulty of providing water services in northern Canada compared to southern Canada. Despite having abundant freshwater resources, difficulties persist in providing consistent and reliable access to drinking water services, as reflected in an over-dependence on trucked water deliveries in remote communities. Additionally, much of the freshwater resources in northern Canada are inaccessible due to the remoteness of the water sources or a lack of adequate infrastructure.

Greater disparity between northern and southern Canada was found in energy and food security. In terms of energy security, northern Canada would rank 90th globally, with an energy pillar score of 51.88, 87 spots behind Canada, which ranked 3rd, with a score of 84.81. This indicates that energy insecurity is significantly more prevalent in northern Canada than it is in southern Canada. Although all of northern Canada has access to electricity and ranked high in electric power consumption, it ranked low in renewable energy consumption, CO₂ emissions per capita, and net energy imports. Whereas Canada is a net exporter of energy, energy imports accounted for 82.5% of energy

use in northern Canada. Furthermore, although 65% of northern Canada's electricity output is generated from renewable sources (primarily hydro), northern Canada accounts for less than 0.5% of Canada's total electricity production [17]. These findings highlight northern Canada's reliance on imported non-renewable energy sources, as the remoteness of many communities makes it prohibitively costly or impossible to connect them to electricity grids, in which case they depend on diesel-fueled generators to meet their energy needs.

Table 3. WEF Nexus Index and resource pillar scores. Rank if included among the global sample (N = 170) in parentheses.

Region	WEF Nexus Index	Water Sub-Index	Energy Sub-Index	Food Sub-Index
Canada	75.51 (5)	68.50 (42)	84.81 (3)	73.22 (13)
Northern Canada	57.50 (67)	72.42 (22)	51.88 (90)	48.22 (113)
Nunavik	60.66 (54)	73.92 (19)	57.28 (68)	50.78 (101)
Northwest Territories	57.59 (67)	72.44 (22)	50.58 (100)	49.74 (107)
Yukon	56.56 (69)	66.64 (51)	59.08 (56)	43.96 (129)
Labrador	55.61 (80)	68.98 (40)	53.14 (82)	44.71 (129)
Nunavut	50.52 (107)	67.54 (48)	36.62 (141)	47.39 (117)

Lastly, whereas Canada's food pillar score ranked 13th (73.22), northern Canada's food pillar score would rank 113th (48.22), 100 spots behind Canada. This difference is the greatest among the three WEF pillars, indicating the greatest discrepancy in WEF resource security between northern and southern Canada is in food security. Northern Canada ranked relatively low in several indicators, including prevalence of undernourishment, prevalence of obesity, average protein supply, and average dietary energy supply adequacy. Although cereal yield data could not be found to include in our analysis, short summers and cold climate conditions make local agricultural production infeasible throughout most of northern Canada. Therefore, the majority of retail food goods, much of which are processed to keep long shelf lives, are shipped in from southern Canada at considerable costs, resulting in higher food prices. These findings highlight a two-sided problem of food insecurity in Northern Canada. The undernourishment, average protein supply, and average dietary energy supply adequacy statistics are indicative of the limited access to and availability of affordable and healthy food options that are commercially available, while the high obesity rate is a result of the relatively more affordable, yet low quality, food options available in grocery stores that give rise to deleterious health effects.

4.2. Territorial/Provincial Sub-Regional Results

Following the northern and southern Canada WEF security assessment, we found that considerable intra-regional variability of WEF security also exists within northern Canada. If the five northern Canada regions were included in the global analysis independently, Nunavik would rank 54th, the highest among the five northern regions, followed by Northwest Territories (67th), Yukon (69th), Labrador (80th), and Nunavut (107th) (see Table 3 above).

As was the case for northern Canada as a whole, access to and the availability of water received the highest scores and rankings for each of the five northern regions. All five regions had at least 98% of people using safely managed sanitation services. Additionally, each region had annual internal freshwater withdrawals of 0.1% or less and ranked highly

in renewable internal freshwater resources per capita, indicating the availability of freshwater resources throughout northern Canada. Between the five northern regions, Nunavik had the highest water pillar ranking, and Yukon had the lowest. Yukon's relatively low water security score can partially be attributed to having the lowest percentage of people using at least basic drinking water services and the lowest environmental flow requirements.

Whereas Yukon scored the lowest among the five regions in terms of water security, it ranked first among the five regions in terms of access to and availability of energy resources. The difference between Yukon's energy pillar score and rank (59.08, 56th) and Nunavut's (36.62, 141st) marked the greatest disparity between the highest and lowest ranking regions among the WEF pillars and indicates that energy insecurity is considerably more prevalent in Nunavut than it is in the other northern regions. Although all of Nunavut has access to electricity, renewable energy consumption and renewable electricity output were nearly zero, as the territory has no electrical grid, and it is wholly reliant on diesel fuel imports to meet its energy needs [18]. These conditions are compounded by high electric power consumption per capita, which is common in cold climate regions.

The food pillar was the lowest ranking resource pillar for every region except Nunavut. Each region ranked low in terms of average dietary energy supply, prevalence of obesity, and prevalence of undernourishment. Although Nunavik ranked the highest among the five northern regions, its global rank would be 101st (50.78), placing it between the Maldives (50.8) and Jamaica (50.7). Furthermore, the difference between the highest (Nunavik) and lowest (Nunavut) ranked region in northern Canada would be only 28 spots, which is the smallest disparity of the three WEF pillars. This seems to indicate that food insecurity is a challenge throughout northern Canada and is experienced more or less uniformly in each region.

5. Discussion

The WEF nexus has emerged as a prominent framework for guiding integrated resource management strategies, assessing resource security, and monitoring progress towards the WEF-related SDGs. WEF nexus-based research has highlighted the importance of treating WEF sectors as a multi-centric, interconnected system in order to achieve more efficient resource planning outcomes. Recently, the Global WEF Nexus Index was compiled in an effort to measure WEF security in 170 nations worldwide. Based on the compilation of 21 WEF indicators, the WEF Nexus Index serves as an important resource for measuring country-level WEF security and tracing progress toward the attainment of WEF-related SDGs.

As valuable as the WEF Nexus Index has proven, an acknowledged limitation is that it obscures regional and sub-regional variabilities, especially among less populated regions. The aggregation of country-level data has shown to be useful, but the experiences and conditions of those most vulnerable to WEF insecurities can go unobserved when using national data only. This has proven to be the case for northern Canada. Our results indicated that while northern Canada ranked higher than Canada in terms of water security, it ranked lower in energy and food security. We also found that WEF nexus security varies within northern Canada between provinces and territories, highlighting the need for regional-level WEF nexus assessments.

Intra-regional WEF security differences in northern Canada are influenced by a host of geographic, demographic, and societal factors. In particular, remote Indigenous communities are subject to poor WEF security provisions relative to larger northern city centers (i.e., Whitehorse, Yukon or Yellowknife, NWT). For example, there are 85 remote communities in northern Canada that are not connected to an electrical grid and that are reliant on diesel-fueled power generation. These communities have a combined population of 69,477 (43% of the total population in our study area), and only one community is not predominantly Indigenous [18]. These conditions create additional vulnerabilities in their energy security that are not shared by grid connected communities. Similar conditions can be found in water security provisions. In 2018, seven (21%) communities in Northwest Territories were

subject to boil water advisories. Each of these communities was remote, predominantly Indigenous, and relied exclusively on trucked water supplies [19]. Intra-regional inequities also exist in community access to healthy, nutritious, and affordable foods. In the community of Old Crow, Yukon, residents pay an average of CAD 496/week for a healthy food basket. This same food basket can be purchased for CAD 206 in the Yukon's capital city of Whitehorse [20]. These cost differences can be attributed to the added expense of northern transport (estimated >20%) [21] and higher electricity rates (roughly 84%) [22], both of which demand increased energy inputs. When WEF data are aggregated at the territorial level, the intra-regional variability that exists is inadequately captured. For these reasons, the further disaggregation of WEF data is needed to provide a clearer understanding of how WEF insecurities are being experienced. Failing to account for these differences, and the intersectionality of social and economic conditions may further propagate discrimination and disadvantage of those who are already most vulnerable.

Accounting for intra-regional variability will be particularly important, as northern Canada experiences the deleterious effects of climate change. Although southern Canada is not immune to the effects of climate change, northern Canada is expected to feel the impacts of climate more profoundly. Canada has responded to climate threats through various strategies, including pricing carbon pollution, investment in public transit, advancements in zero emission vehicles, expanding the electric grid, and offering employment training programs to transition to a clean energy economy [23]. However, many of these strategies are not applicable to northern Canada, and the need for northern specific adaptive capacities is becoming increasingly apparent as the effects of climate change put the already vulnerable conditions of WEF resources at further risk. For example, in Nunavut, climate change has led to decreases in water quality and quantity, damage to water and sanitation infrastructure, and water maintenance and treatment issues [24]. The Northwest Territories anticipates climate change to have similar negative impact on water quality and quantity, with detrimental changes caused by increased temperatures, extreme weather events, variability in precipitation, and impacts to critical infrastructure [25]. Climate change is also contributing to water scarcity, with some northern cities preparing for water shortages by 2024 [26]. The recent events in Iqaluit, Nunavut, demonstrate how vulnerable northern WEF systems are to disturbances. In this case, an undetected leakage of petroleum into Iqaluit's water supply has rendered the city's water undrinkable and has required tens of thousands of liters of bottled water to be airlifted in. While still being investigated, the contamination is being attributed to thawing permafrost that may have either liberated a previous oil spill or has damaged existing infrastructure [27]. Accounting for climate-related impacts will be essential in developing sustainable, integrated WEF resource management strategies in the future. If these conditions persist and adaptive responses fail to be implemented, one can expect further disparity in WEF security between Canada's northern and southern regions.

A potential limitation of our analysis was that certain indicators in the WEF Nexus Index were not relevant, applicable, or potentially misrepresented WEF security in northern Canada. For example, the cereal yield per hectare indicator is representative of conventional agricultural food procurement methods that are not feasible throughout most of northern Canada. The annual freshwater withdrawals and renewable internal freshwater resources per capita indicators suggested that northern Canada had strong water security. However, given the vast land area and sparse population of northern Canada, these indicators could overestimate water availability by capturing inaccessible or unused remote water systems. Although the WEF Nexus Index indicators are useful for making global comparisons in WEF security, they can miss important drivers of localized WEF security systems that are dependent on geographic, climatic, economic, and cultural factors. As the spatial scale of analysis decreases, there is an increased need for regionally specific and relevant indicators that reflect local WEF systems. We maintained the global WEF Nexus Index indicator framework in our analysis to make direct comparisons to Canada's country level data and the global dataset. However, future regional WEF nexus assessments should include

regionally applicable indicators in order to accurately measure and portray WEF security. Using the above examples, subsistence wildlife, fish, and seafood harvesting is a common method for procuring nutritious country foods in far north regions, particularly among Indigenous populations. An indicator measuring subsistence and commercial harvesting could therefore capture an important aspect of food security in northern Canada. Similarly, a water use and deliveries per capita indicator could more accurately represent the amount of water readily available for human use in northern Canada.

In summary, our findings show significant disparity in WEF security between northern and southern Canada, demonstrating how national-level data, and data aggregation in general, can obscure resource insecurities in vulnerable, less populated regions. By highlighting these differences, we hope that this research can aid decision-makers in developing informed, regionally specific, and integrative resource management strategies and policy responses to better achieve inter-regional WEF security. We are also hopeful that this research will motivate others in the research community to examine how WEF insecurities are experienced at finer scales and to help ensure future interventions remedy, rather than amplify, existing WEF-related inequalities.

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