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Uncovering the economic impact of thawing arctic permafrost: Exploring GDP production in a changing landscape

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ABSTRACT

Permafrost has undergone rapid warming since the 1980s. The resulting permafrost thaw has already led to economic consequences, for example coastal retreat requiring the relocation of several settlements, engineering costs necessary to repair or avoid collapses of buildings, airports, railways, roads, and pipelines, etc. Calculating Gross Domestic Product (GDP) at subnational scales, we estimate the total economic value and their potential loss in the Arctic Circumpolar Permafrost Region (ACPR) that is produced on permafrost cover, and as such which is likely to be exposed to hazards from permafrost thaw. Our results give a value of €83.9–189.3 billon in 2017. About 91–92 % of this total GDP is produced on the Russian territory. In the ACPR, natural resource extraction seems to be a key driver of GDP. This means many countries depending on Russian ACPR exports will be in troubles in case of reduced economic production due to permafrost thaw. To avoid international economic disruptions, public authorities in the ACPR countries should be willing to pay a certain percentage of the total permafrost GDP to adapt and reduce the economic impacts of permafrost thaw. We estimate the adaptation cost to be between 0.01 % and 14.6 % of the total permafrost GDP.

1. Introduction

Arctic regions have received increased attention owing to the unprecedented and rapid environmental changes they experience (Box et al., 2019; Vincent, 2020). One type of major changes is the one associated with permafrost, which covers approximately 20–25 % of the northern hemisphere and 17 % of the Earth's exposed land surface (Biskaborn et al., 2019; Obu, 2021). Permafrost is ground with a temperature remaining at or below 0 °C for at least two consecutive years. The permafrost is highly sensitive to changes in climate due to the vulnerability of frozen ground to air temperature. The Arctic air temperature has increased by 2.7 °C between 1971 and 2017, and nearly four times faster than the globe (Rantanen et al., 2022; Box et al., 2019; Schaefer et al., 2012; Katsov and Semenov, 2014). Thereby, permafrost has undergone rapid warming, with temperatures typically increasing by 0.3–1.0 °C per decade since the 1980s (Hjort et al., 2022; Smith et al., 2022). Permafrost landscapes are therefore undergoing significant degradation (warming and thawing), with repercussions on ecosystem functioning (Heijmans et al., 2022), greenhouse gas emissions (Miner et al., 2022; Voigt et al., 2020; McGuire et al., 2012), geomorphological processes (Jones et al., 2022; Hjort et al., 2022) and hydrology (Walvoord and Kurylyk, 2016).

Permafrost thaw, which involves a rise in ground temperature accompanied by the melting of ground ice, can lead to a range of negative impacts. These may include ground subsidence, landslides, soil volume loss through bank and coastal erosion, increase in thermokarst lakes or thaw slumps shifting the ecosystem from terrestrial to aquatic (Lewkowicz and Way, 2019; Stolpmann et al., 2021; Bartsch et al., 2021; Dupeyrat et al., 2011; Lantuit et al., 2011). Coastal erosion caused by permafrost thaw is already affecting human settlements and infrastructures (Anisimov, 2017; Anisimov et al., 2010; Ramage et al., 2021). Essential provisioning services provided by the ecosystem to Arctic communities are declining due to permafrost thaw, e.g. reindeer, game, fish, birds and seals that are harvested for food, fur coat or feather

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(Vihervaara et al., 2010; Ramage et al., 2022). Another major threat for Arctic populations affected by permafrost thaw is the mobilization, transport, and accumulation of environmental contaminants and pathogens in the food web such as release of mercury (Schuster et al., 2018) or emerging human infectious diseases (Waits et al., 2018). Climate warming and permafrost thaw also alter vegetal species; which may alter overall ecosystem function (Berner et al., 2020).

All these permafrost-induced changes have many economic consequences (Streletskiy et al., 2023). Changing climate conditions may benefit some aspects of Arctic economies, e.g., a warming climate is likely to reduce heating costs (Katsov and Semenov, 2014); diminishing sea-ice extent has the potential to foster economic development along the coasts; the northward advance of land suitable for agriculture will allow sustainable regional development aimed at more intensive use of local resources (Anisimov, 2017); reduction of the sea ice in the Arctic will lead to a more navigable northern sea route (Khon and Mokhov, 2010); and increased water resources and a longer ice-free season on rivers will help water transport of passengers and commodities since in the absence of the developed road network in the Arctic, rivers serve as transportation corridors (Katsov and Semenov 2014). However, the potential benefits of permafrost thaw may be overshadowed by a host of new challenges (Anisimov, 2017). These include the intensification of coastal erosion, shortened winter road operational seasons due to softer unfrozen grounds (Stephenson et al., 2011), and a decline in the bearing capacity of thawing permafrost, which can no longer support existing infrastructure as before (Shiklomanov et al., 2017). Additionally, coastal retreat may require the relocation of several settlements, and increasing engineering costs will be necessary to repair or avoid collapses of buildings, airports, railways, roads, and pipelines due to thermokarst and differential ground subsidence caused by permafrost thaw. These changes also pose growing difficulties for local populations in conducting subsistence activities and benefitting from provisioning ecosystem services, among other challenge.

Permafrost areas in the northern hemisphere host a significant number of critical infrastructure, including at least 120,000 buildings, 40,000 km of roads, and 9500 km of pipelines (Hjort et al., 2018). Unfortunately, negative effects of permafrost thaw are already being observed (Streletskiy, 2021), resulting in damage to numerous buildings as reported by Grebenets et al. (2012). Moreover, with projections indicating continued warming of permafrost, the cumulative problems of infrastructure damage can be exacerbated (Streletskiy et al., 2019; Suter et al., 2019), with up to 69 % of fundamental circumpolar infrastructure (residential, transportation and industrial infrastructure) at risk by mid-century (Hjort et al., 2018, 2022). Several authors have provided estimations of the economic impacts of permafrost thaw on these infrastructures (Larsen et al., 2008; Streletskiy et al., 2019; Porfiriev et al., 2019; Badina, 2021). However, none of these economic studies have provided an estimation of the total economic value (and their potential loss) that is produced on permafrost in the northern circumpolar permafrost region. While some authors have estimated the potential global economic impact of permafrost thaw due to carbon dioxide (CO_2) and methane (CH_4), they often omit key economic sectors in the Arctic region (such as tourism, fishing, and shipping) (*inter alia*, Hope and Schaefer, 2016; Chen et al., 2020; Yumashev et al., 2019). They used PAGE09 and PAGE-ICE models, which omit damages caused by permafrost thaw to infrastructures and the foundations of buildings in the Arctic (Hope and Schaefer, 2016; Chen et al., 2020). These omissions highlight the need for a more comprehensive analysis of the economic impacts of permafrost thaw that takes into account the unique characteristics and dependencies of the Arctic region.

The only pan-Arctic estimation of the costs of permafrost degradation focusses on critical infrastructure such as roads, railways, pipelines, ports, airports and buildings (Suter et al., 2019). The estimated lifecycle replacement costs to maintain infrastructure on permafrost will require US $15.5 billion by 2059 under RCP8.5[1] (Suter et al., 2019). Linear infrastructure (roads, railways and pipelines) is expected to be the most affected, with pipelines being the most vulnerable (Hjort et al., 2022). In addition, damage associated with thaw subsidence and a decrease in permafrost bearing capacity is estimated to add an additional US $21.6 billion to those associated with maintenance costs (Suter et al., 2019). However, these values are largely constrained by the availability of infrastructure data, especially in the case of Russia (Hjort et al., 2022).

This paper aims to fill this knowledge gap by providing a comprehensive assessment of the economic value produced on permafrost. Specifically, we present the first pan-Arctic estimation of the Gross Regional Product (GRP) produced on permafrost, which is the Gross Domestic Product (GDP) estimated at sub-national levels. By combining spatial data showing the permafrost extent data with GRP data and settlement data, we estimate the GRP value produced on each type of permafrost (continuous, discontinuous sporadic, and isolated patches permafrost) in each Arctic Region. This allows us to estimate the share of the total Arctic permafrost GRP which is most likely to be exposed to hazards from permafrost thaw. In Section 2, we present the data and case study area, section 3 develops the method, Section 4 presents our results, which are discussed in Section 5 to answer the question: how much should the Arctic country governments be willing to pay to mitigate the impact of permafrost thaw on resource-based industries in the north? A conclusion is provided in Section 6.

2. Data and case study area

This paper covers the Arctic Circumpolar Permafrost Region (ACPR), which is home to 1785 settlements with a total population of 6.7 million inhabitants in 2016–2017 located in 8 arctic countries – Russia, Canada, United-States (Alaska), Norway, Denmark with the autonomous territory of Greenland, Finland, Sweden and Iceland. Our data include the 25 subnational regions of the ACPR and their 1785 human permafrost settlements. The GRP data in 2017 for the 25 subnational regions (Table 1) were collected from the database provided online by OECD.Stat (accessed in 2021). For Greenland, data on GRP per capita were missing in the database. We estimated them based on data from the National statistical office (Statistics Greenland: http://www.stat.gl/). Population data of the 1785 settlements in 2016 or 2017 (depending on last year available data) have been collected from population censuses as well as administrative and register data at settlement level – the population data sources we used are those listed in Ramage et al. (2021, page 26). Although updated population and GRP data have since become available, our analysis focuses on pre-COVID-19 and pre-Ukraine war conditions, offering insight into the demographic and economic landscape prior to these significant events. Future research could incorporate the latest data to build on our findings and track subsequent changes. As in Ramage et al. (2021), permafrost type data (continuous, discontinuous sporadic, and isolated patches permafrost) was collected from Obu et al. (2019), where the permafrost extent for each type is based on the modeled temperature at the top of the permafrost (TTOP model) for the period 2000–2016. The permafrost extent is available at the circum-Arctic scale, with a resolution of 1 km^2.

By collecting data at a local level, we can better reflect the spatial variability of Arctic climate changes. This is important as increases in permafrost temperatures can vary significantly across Arctic regions

[1] The RCP scenario 8.5 simulated by the IPCC (2014, p. 179) corresponds to the scenario SSP5-8.5 simulated by the IPCC et al., 2021b, p. 14), that is, a scenario in which an increase of 2.5 °C above preindustrial levels would be reached somewhere between 2041 and 2060.

Table 1
Gross regional product (GRP) per capita in the 25 arctic subnational regions.

Column	a	B	c
A_CODE	Country	Subnational regions r ($r = 1, \ldots, 25$)	GRP per capita in 2017 (Euros in PPP at 2017 prices)
AK	United-States	1. Alaska	62,004
NL	Canada	2. Newfoundland and Labrador	45,226
NU	Canada	3. Nunavut	58,818
QC1	Canada	4. Quebec	36,940
NT	Canada	5. Northwest Territories	74,398
YT	Canada	6. Yukon	53,762
FI19	Finland	7. Lapland	39,822
GL	Greenland	8. Greenland	45,306
IS	Iceland	9. Iceland	48,844
NO20	Norway	10. Finnmark	44,079
NO19	Norway	11. Troms	46,129
/	Norway	12. Svalbard (Norvegian part)	44,519[a]
SE25	Sweden	13. Norrbotten	47,444
/	Russia	14. Svalbard (Russian part)	65,565[a]
RU21	Russia	15. Komi republic	24,958
RU22	Russia	16. Arkhangelsk Oblast	23,547
RU23	Russia	17. Nenets Autonomous Okrug	231,069
RU28	Russia	18. Murmansk Oblast	21,681
RU522	Russia	19. Khanty-Mansi Autonomous Okrug (also called Yugra)	78,169
RU523	Russia	20. Yamalo-Nenets Autonomous Okrug	168,345
RU65	Russia	21. Krasnoyarsk Krai	24,052
RU70	Russia	22. Sakha Republic (Yakutia)	34,955
RU71	Russia	23. Kamchatka Krai	23,513
RU75	Russia	24. Magadan Oblast	39,994
RU78	Russia	25. Chukotka Autonomous Okrug	50,929

[a] Note: in OECD.Stat (accessed in 2021), data on GRP and GRP per capita statistics were missing for Svalbard. We could not find data neither on the Norway national statistical office. Thus, we estimated GRP per capita for Svalbard using the average GRP per capita of arctic regions in Norway, i.e., Finnmark and Troms for the Norwegian part of the archipelago (€44,519 in PPP at 2017 prices), and the average of Arctic regions in Russia, i.e., the last 11 rows in Table 1 for the Russian part (€65,565 in PPP at 2017 prices). For Greenland, data were also missing in OECD.Stat (accessed in 2021). Thereby, GRP per capita were estimated based on data from National statistical offices: Statistics Greenland (http://www.stat.gl/).
Source of data: OECD.Stat (accessed in 2021).

(IPCC et al., 2021a, chapter 2, p. 348). Our approach allows us to capture this variability and provide a more accurate assessment of the economic impacts of permafrost thaw in each region.

There is also spatial variability in human settlements and infrastructures. Almost 65 % of Russian land area is underlain by permafrost (Zhang et al., 2008). These regions contain a large number of settlements and high population density (Hjort et al., 2022). This explains that more than 60 % of settlements and nearly 90 % of the population in Arctic permafrost areas are located in Russia (Ramage et al., 2021). By the beginning of the 21st century, many buildings on permafrost had deformations: between 10 % and 80 % of structures depending on cities (Hjort et al., 2022). Substantial reductions in foundation stability have also been observed: for example, in north-west Siberia, increasing permafrost temperatures and active layer thicknesses have reduced foundation support by 17 % on average over 1990–2010 relative to 1960–1990, reaching up to 45 % reductions in some locations (Streletskiy et al., 2012).

In Svalbard (Norway and Russia) and Greenland (Denmark), a few notable settlements and other infrastructure are located on Arctic permafrost (Ramage et al., 2021; Harris et al., 2009). However, in these locations, thaw damage is less extensive because the ground ice content is reduced, the type and size of engineered structures is different from Russia, and there is higher investment in construction and maintenance (Humlum et al., 2003; Phillips et al., 2007; Jaskólski et al., 2018; Duvillard et al., 2019; Jungsberg et al., 2022).

In North America, more than 50 % of Canadian and 80 % of Alaskan land surfaces are characterized by the presence of permafrost (Hjort et al., 2022). Its sparse population (representing 7 % of the entire Arctic permafrost area population – Ramage et al., 2021) and its abundant resources depend on horizontal or linear transportation infrastructure (Doré and Zubeck, 2009). These include 6800 km of road, 270 airstrips (Hjort et al., 2018) and infrastructure such as the Trans-Alaska Pipeline System. Structural degradation is becoming increasingly evident along these infrastructures in northern Canada and Alaska (Hjort et al., 2022).

3. Method

Our objective is to approach an estimation of the direct economic impact of permafrost thaw by measuring potential GDP losses at subnational regional levels in the ACPR. A common indicator for measuring the level of economic activities at regional scale is the Gross Regional Product (GRP), that is, the Gross Domestic Product (GDP) computed at sub-national levels. GRP is a monetary measure of the market value of all the final goods and services annually produced by economic activities in a subnational region. GRP also measures regional value-added (plus taxes on production), i.e. the remuneration paid to the owners of the factors of production (employees' wages, shareholders' dividends, rents paid to owners of buildings and land) from revenues generated by the sale of goods and services (Mikheeva, 2020), which reflects the economic output of the region (Fedorov and Kuznetsova, 2020). Dividing GRP by the number of inhabitants living in the region gives the GRP per capita. It reflects the economic output produced on average per inhabitant as well as the average income earned by each inhabitant (Kramin et al., 2014) and similar to GDP, GRP can be calculated using either the income approach or the production approach. Both approaches give exactly the same result given that all the receipts earned from selling economic production is used to pay incomes such as wages and salaries to employees, rents to owners of buildings, dividends to shareholders, etc. (Vu, 2012; Lee, 2011).

We computed a database providing the GRP per capita (Table 1) for each of the 25 arctic sub-national regions located on permafrost. We combined this database with the data from Obu et al. (2019) which provides a permafrost type layer geolocating continuous, discontinuous sporadic, and isolated patches permafrost (see Section 2). The combined database is displayed in Table 2 for selected settlements as an example (the full database for the 1785 permafrost settlements is available in supplementary materials here: https://doi.org/10.5281/zenodo.14981372)).

Not all the 1785 settlements located in arctic circumpolar permafrost regions will be affected by permafrost thaw since not all infrastructures, buildings, and equipment are built on permafrost (Streletskiy et al., 2019). The percentage of permafrost coverage in the settlements varies according to permafrost types (continuous, discontinuous sporadic, and isolated patches permafrost) as can be seen in Fig. 1. We estimate the total GRP produced on permafrost in the ACPR with Eq. (1), which computes a weighted estimation of GRP produced on permafrost considering that only a certain percentage of the settlements surface areas are built on different types of permafrost. Equation (1) consists in multiplying the GRP of each of the 1785 settlements i (Table 2) by the percentage of coverage of permafrost type j observed in settlement i:

$$\begin{cases} GRPpermafrost_{low} = \sum_{i=1}^{1785} GRP_i^r \times \text{Permafrost\%}_{i,j}^{Lower\ estimate} \\ GRPpermafrost_{high} = \sum_{i=1}^{1785} GRP_i^r \times \text{Permafrost\%}_{i,j}^{Higher\ estimate} \end{cases} \quad \text{Eq. (1)}$$

Table 2

GRP and permafrost types in ACPR settlements (Arctic Circumpolar Permafrost Region) of the 8 Arctic countries in 2017. Note: few examples are displayed here as an example. The full table is made of 1785 data rows, which cover all ACPR settlements, and is available in supplementary materials (available on Zenodo here: https://doi.org/10.5281/zenodo.14981372). Data sources: GRP in settlements with permafrost coverage (column h) is obtained for each settlement multiplying GRP per capita in 2017 (column c in Table 1) with population in 2016–2017 (column f) and permafrost coverage presence [0, 1] values (column g_{tot}). Population in 2016–2017 have been collected from population censuses as well as administrative and register data at settlement level – see Ramage et al. (2021, page 26) for the full list of sources. Permafrost type data (columns g_{tot}, and g_1 to g_4) have been collected from Obu et al. (2019).

Column	d	e	f	g_{tot}	g_1	g_2	g_3	g_4	$h = f \times g_{tot} \times c_{Table\ 1}$
Subnational regions *r (r = 1, …, 25)*	Countries	Settlement *i (i = 1, …, 1785)*	Population in 2016–2017 (number of inhabitants)	Permafrost coverage presence	Continuous 90–100 %	discontinuous 50–90 %	Sporadic 10–50 %	Isolated patches 0–10 %	GRP in settlements with permafrost coverage (Euros in PPP at 2017 prices)
1. Alaska	United States	1. Adak city	308	0	0	0	0	0	0
1. Alaska	United States	2. Akhiok city	88	0	0	0	0	0	0
…	…	…	…	…	…	…	…	…	…
5. Northwest Territories	Canada	373. Aklavik, HAM	590	1	1	0	0	0	43,895,189
…	…	…	…	…	…	…	…	…	…
5. Northwest Territories	Canada	389. Inuvik	3240	1	1	0	0	0	241,051,548
…	…	…	…	…	…	…	…	…	…
8. Greenland (Aasiaat)	Denmark	644. Kitsissuarsuit	59	1	0	1	0	0	2,673,068
…	…	…	…	…	…	…	…	…	…
9. Iceland	Iceland	780. Reykjavik	122198	0	0	0	0	0	0
…	…	…	…	…	…	…	…	…	…
10. Finnmark	Norway	814. Karasjok	1844	1	0	0	0	1	81,280,852
…	…	…	…	…	…	…	…	…	…
12. Svalbard (Norvegian part)	Norway	907. Longyearbyen	2145	1	1	0	0	0	95,492,295
12. Svalbard (Norvegian part)	Norway	908. Pyramiden	428	1	1	0	0	0	19,053,940
…	…	…	…	…	…	…	…	…	…
13. Norrbotten	Sweden	1772. Sjulsmark	351	0	0	0	0	0	0
…	…	…	…	…	…	…	…	…	…
25. Chukotka Autonomous Okrug	Russia	1785. Vayegi	420	1	0	1	0	0	21,390,359

where $GRPpermafrost_{low}$ and $GRPpermafrost_{high}$ are respectively the lower and the higher estimate of total GRP produced on permafrost in the ACPR; GRP_i^r is the GRP of settlement i in region r as calculated in last column of Table 2; Permafrost$\%_{i,j}$ is the percentage of surface area in settlement i (for $i = 1, \ldots, 1785$) that is covered by permafrost and it takes 4 range of percentage values according to permafrost type j observed in the settlement i (for $j = 1., \ldots, 4$): $j = 1$ in continuous permafrost areas and the range is 90 %–100 % (lower and higher estimate, respectively), $j = 2$ in discontinuous permafrost areas and the range is 50–90 %, $j = 3$ in Sporadic permafrost areas and the range is 10–50 %, %, $j = 4$ in isolated patches permafrost areas and the range is 0–10 %.

Our approach currently overlooks the differences in economic and socio-economic activities among settlements within the same region, as all economic data are provided at the regional level. This limitation means that we do not capture the localized exposure of economic activities to melting permafrost. A more comprehensive approach would involve exploring the Gross Regional Product (GRP) produced in each settlement, necessitating a detailed examination of all 1785 communities to ensure our methodology appropriately reflects the economic landscape. However, this is extremely difficult to carry out due to lack of data. This limitation is further explored in the discussion section below, along with potential avenues for future research to address this drawback. While our approach may lack precision at the settlement level, it provides a valuable spatial overview at the international level across the 8 Arctic countries. Thus, the lower accuracy at the local scale benefits our ability to gain insights on a broader scale. Our results can be considered a third-best option in the context of data limitations. The ideal scenario would involve a study utilizing economic data from each of the 1785 settlements (which is currently unavailable). The second-best option would involve tracking economic data by economic sector over time across the 25 Arctic regions; however, such a database does not exist. Consequently, our approach entails disaggregating the Gross Regional Product (GRP) of each of the 25 regions, allocated proportionally based on the size of the local population in the 1785 settlements, which represents the third-best feasible solution given the data constraints.

The results of Eq. (1) are displayed on Fig. 2 and presented in Section 4.

4. Results

4.1. Estimation total GRP produced on permafrost in the ACPR

Equation (1) estimates the total GRP on permafrost cover (including continuous, discontinuous, sporadic and isolated patches permafrost) in the ACPR to be between €83.9 billon (lower estimate) and €189.3 billion (higher estimate) in 2017 (€ in PPP at 2017 prices as all monetary values in this paper unless specified otherwise).

Fig. 2 displays results from Eq. (1) on a pie chart. Across all subnational regions in the ACPR, the top three regions with the highest value of GRP on permafrost are the Russian regions of Yamalo-Nenets (€32–67 billion), Khanty-Mansi Autonomous Okrug (€27–54 billion), and Sakha republic (also called Yakutia, €10–31 billion). These three regions

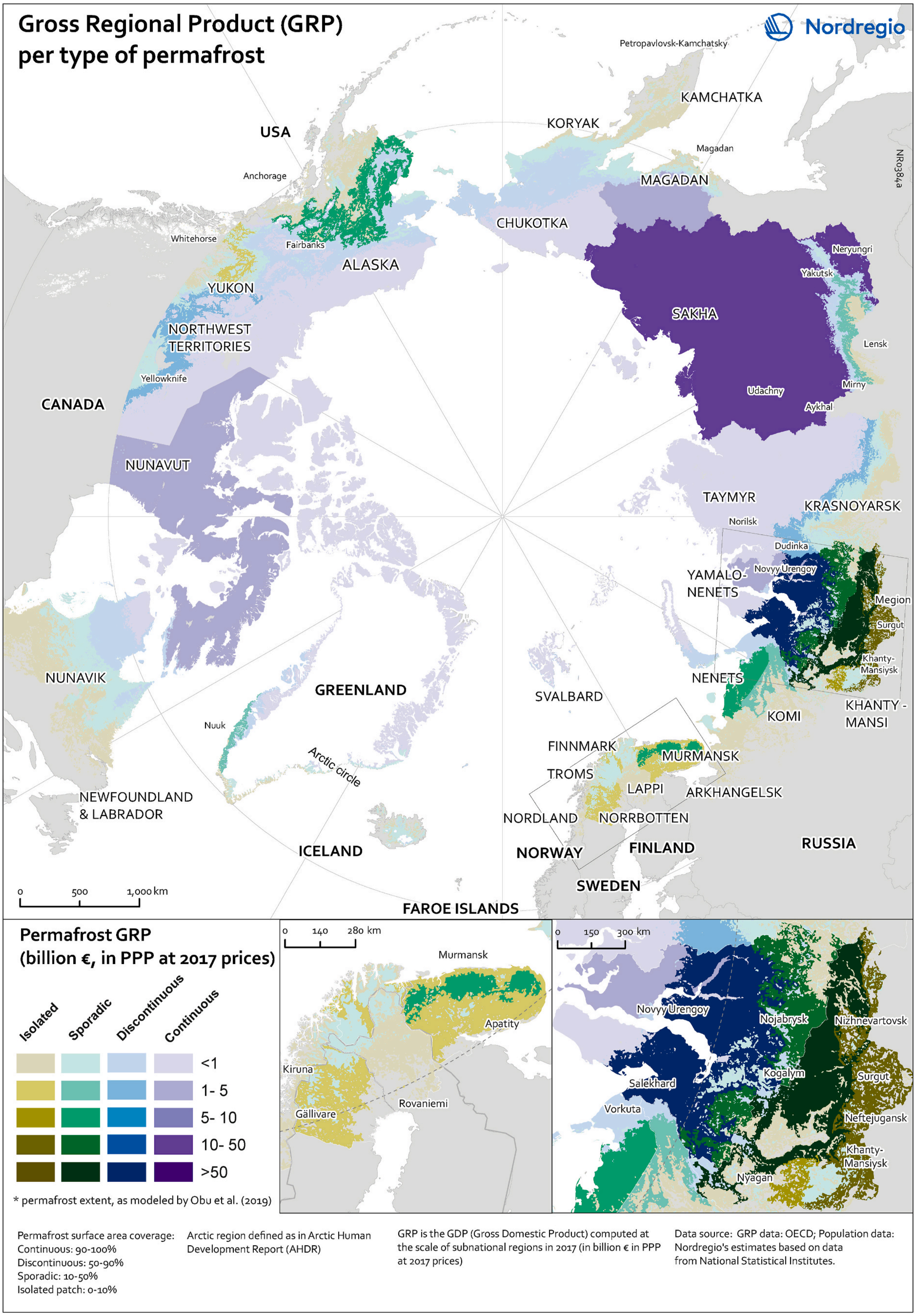

Fig. 1. Map of GRP per permafrost types for each of the 25 subnational regions in the ACPR in 2017 (in billion € in PPP at 2017 prices). Note: GRPs in Fig. 1 are on permafrost areas exclusively, that is, in 25 subnational regions of the ACPR. The 25 subnational regions are listed in Table 1. Source of data to compute the map: OECD.Stat (accessed in 2021), National statistical offices (see the list in Ramage et al., 2021, page 26), Obu et al. (2019).

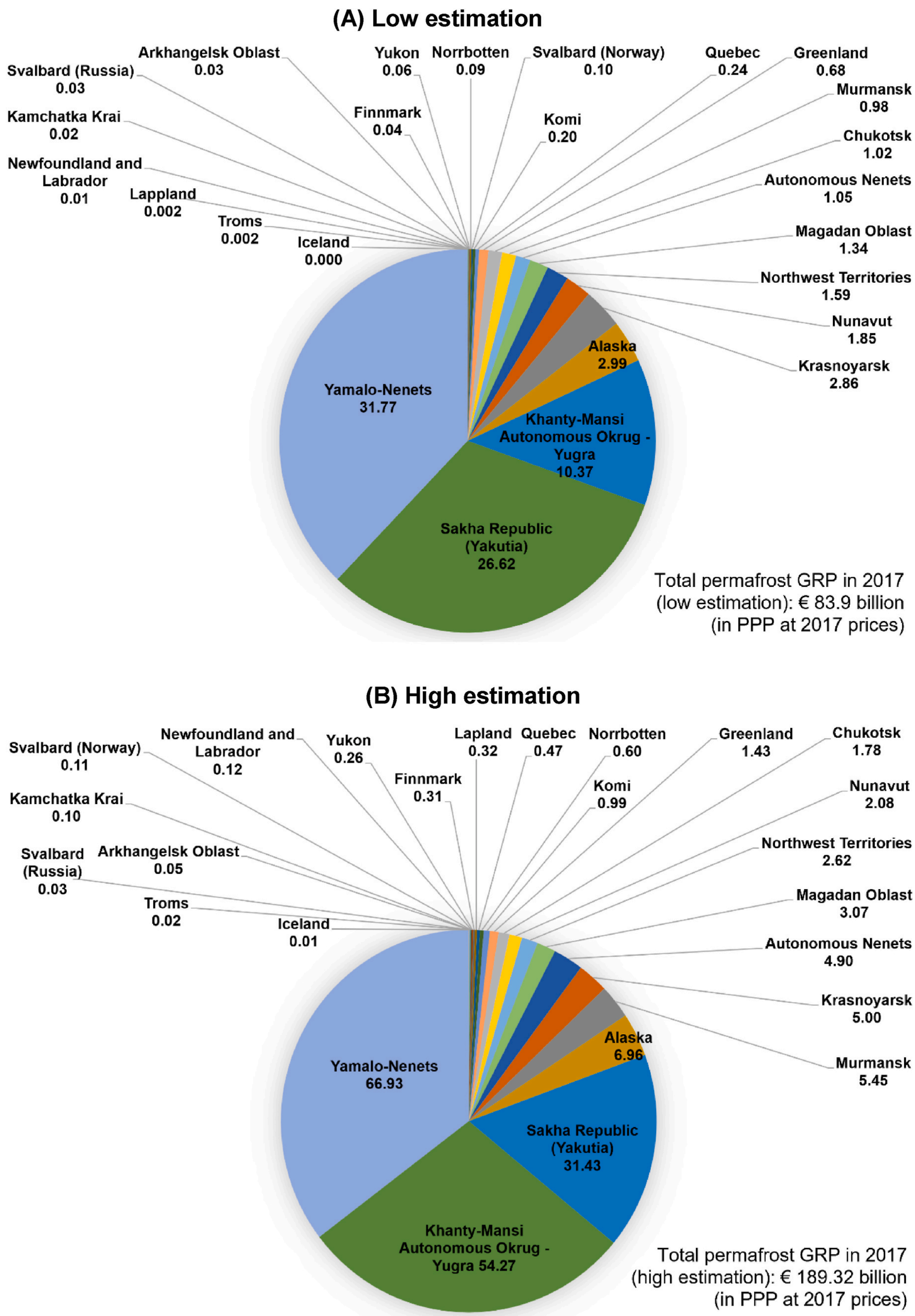

Fig. 2. GRP on permafrost in 2017 in the 25 ACPR subnational regions (in billion € in PPP at 2017 prices). Note: Figures (A) and (B) have been computed using Eq. (1) at the scale of each of the 1785 ACPR settlements. Summing values displayed on this figure across the 25 subnational regions (listed in Table 1) in each ACPR country gives the following values of GRP on permafrost: €76–174 billion in Russia, €3–7 billion in the United-States (Alaska), €4–6 billion in Canada, €0.7–1.4 billion in Denmark (Greenland), €0.09–0.6 billion in Sweden, €0.1–0.4 in Norway, €0.002–0.3 billion in Finland, and €0.00–0.01 billion in Iceland.

together represent between 81 and 82 % of the total GRP produced on permafrost in the ACPR (€ 83.9–189.3 billion, Fig. 2). Please note that the GRP amounts presented may appear unusually high to readers accustomed to values in rubles, US dollars, or euros without PPP adjustments. For cross-country comparison, we converted our GRP data to euros in purchasing power parity (PPP), reflecting the fact that the purchasing power of €1 varies between countries, such as Russia and Canada, due to differences in living costs and income levels. To illustrate, using data from the World Bank data bank website (https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.CD?locations=RU), we can derive a PPP conversion factor for Russia: in 2017, Russia's GDP was US$1.57 trillion at current prices, while in PPP terms, it was US$3.81 trillion (World Bank, accessed in 2024). Thus, GDP in PPP-adjusted dollars is 2.43 times higher than current price US$. This adjustment explains the relatively high GRP values we report. For instance, in Fedorov and Kuznetsova (2020), the GRP of the Yamalo-Nenets Autonomous Okrug is reported as 3084 billion rubles in 2018, equivalent to €44 billion. However, after PPP adjustment, this figure rises to €107 billion.

The Yamalo-Nenets Autonomous Okrug is located primarily on discontinuous permafrost, meaning that 50–90 % of the region's territory contains permafrost in the ground. This may explain why the GRP on permafrost in this region is relatively higher compared to other Arctic regions with less permafrost coverage. In fourth position is Alaska (USA) with a GRP on permafrost estimated to €3–7 billion. This is far less than the top-three Russian regions listed above because in Alaska, the GRP is produced by economic activities mainly located on sporadic and isolated patches permafrost (only 10–50 % and 0–10 %, respectively, of the surface is underlain by permafrost). The bottom-three regions with the lowest value of GRP on permafrost are Finnmark (Norway), Yukon (Canada) and Norrbotten (Sweden). In Finnmark and Norrbotten, this is because only few settlements and economic activities are located on permafrost and they are mostly on isolated patches.

Fig. 3 shows the GRP produced on permafrost in the ACPR as well as the location of active mines and hydrocarbon fields (oil and natural gas). It shows that the regions with the highest GRP on permafrost (Yamalo Nenets, Sakha Republic, and Khanty-Mansi Autonomous Okrug), are also those with the highest number of active mines and hydrocarbon fields (Fig. 3). The regions with the lowest GRP on permafrost (Finnmark, Yukon, and Norrbotten) have a low number of mines and hydrocarbon fields on their territory. This suggests that in the ACPR, natural resource extraction seems to be a key driver of GRP since subnational regions with highest GRPs are also those with the greatest number of mines and hydrocarbon fields.

4.2. Maximum potential avoided damage costs and adaptation costs

This section discusses the maximum potential avoided damage costs and adaptation costs. The avoided damage costs represent the upper bound of potential economic losses due to permafrost thaw by 2050. However, not all economic activities will disappear on these lands as permafrost thaws, meaning that these estimates reflect possible, rather than guaranteed, losses. They should be interpreted as upper-bound estimates of avoided economic losses rather than definitive projections.

4.2.1. In the Russian Arctic

In case adaptation measures would be undertaken to avoid permafrost thaw adverse impacts, the GRP on permafrost estimated in Section 4.1 can be considered a maximum potential avoided damage cost. In environmental economics, avoided damage is a negative economic loss, meaning it constitutes a benefit (Pearce et al., 2006). The comparison between adaptation costs and maximum potential avoided economic damages (i.e., benefits) provides an indicative assessment of whether adaptation could yield net positive economic outcomes (Table 3). However, as the estimated benefits represent upper-bound values, this should not be interpreted as a robust cost-benefit analysis.

To design the comparison, first, we use data from Revich et al. (2022). They estimated the total annual economic cost of adaptation measures needed to overcome the consequences of permafrost thaw (i.e., possible destruction of residential buildings, health-care facilities, and roads built on permafrost) in the Russian Arctic until the year 2050 under the RCP 8.5 global warming scenario from the (IPCC et al., 2014, p. 179). Their estimation ranges from 0.21 % to 0.91 % of the annual Gross Regional Product (GRP) of the Russian Arctic, this represent an absolute amount of US$ 1.1–4.8 billion per year (US$ at 2019 prices). Summing these annual values across all the years between 2022 and 2050 and applying an annual discount rate[2] of 3 % as in Melvin et al. (2017) gives a total cumulative cost of US$ 19–82 billion. Converted into € in PPP at 2017 prices, it gives a total cumulative cost of €45–190 billion.

Porfiriev et al. (2019) provide other estimates of adaptation costs in the Russian Arctic. Under the RCP 8.5 global warming scenario from the (IPCC et al., 2014, p. 179), they estimate the total cost of support and maintenance of road infrastructure owing to permafrost degradation from 2020 to 2050 to reach US$ 7.0 billion for the existing network (without additional development), and US$ 14.4 billion for a modernization scenario incorporating the development goals outlined in the Transport Strategy of Russian Federation (US$ at the prices of the year 2018). Porfiriev et al. (2019) divide this total cost by the 30 years of the period 2020–2050 and obtain an annual cost of US$ 0.23–0.48 billion. In addition, Porfiriev et al. (2021) have estimated costs of residential housing replacement to US$ 0.23–1.84 billion per year over 2020–2050 (US$ at the prices of the year 2018), which corresponds to 14.01–112.27 billion rubles per year at 2018 prices in the original publication by Porfiriev et al. (2021). Summing cost of support and maintenance of road infrastructure and cost of residential housing replacement as Hjort et al. (2022) did, we obtain the total annual cost of US$ 0.46–2.32 billion. Differently to Hjort et al. and Porfiriev et al. we add a discount rate of 3 % as in Melvin et al. (2017) to sum the annual cost across all years over the period 2022–2050. It gives a total adaptation cost to overcome permafrost thaw consequences of US$ 8.08–40.74 billion, which after conversion into € in PPP values at 2017 prices gives a range of € 19–99 billion.

Second, we estimate the maximum potential benefits (i.e., maximum potential avoided GRP losses) that might result from Revich et al.'s and Profiriev et al.'s adaptation measures by summing the GRP annual values displayed in Fig. 2 across all Russian regions in the ACPR (€ 76–174 billion) and across all years over the period 2022–2050 applying an annual discount rate of 3 %. It gives a total maximum potential cumulative benefit range of €1301-2966 billion over 2022–2050. The maximum potential net benefit (= total maximum potential cumulative benefit minus total cumulative costs) still remains high and is estimated between €1111-2921 billion (based on Revich et al.' adaptation costs) or €1202-2948 billion (based on Porfiriev et al.'s adaptation costs) as shown in Table 3.

4.2.2. In the northern American arctic

In Alaska and northern Canada, maintaining stable and safe infrastructure is an important engineering challenge to consider in adaptation strategies as in any other regions of the ACPR. Melvin et al. (2017, p. 125, see last row in their Table 2, third column) estimated the total cumulative costs of proactive adaptation to near-surface permafrost thaw on public infrastructures (e.g., roads, highways, buildings, railways, pipelines, airports) in Alaska under the RCP8.5 global warming scenario. According to their estimations, this cost is expected to reach US $1.3–3.0 billion over 2015–2099 (US$ at prices of the year 2015 with a

[2] Discount rates are applied in economic forecast modeling to consider future inflation, individual preferences for present time and uncertainty which is inherent to any future event estimation. This allows to compare future monetary values with present values.

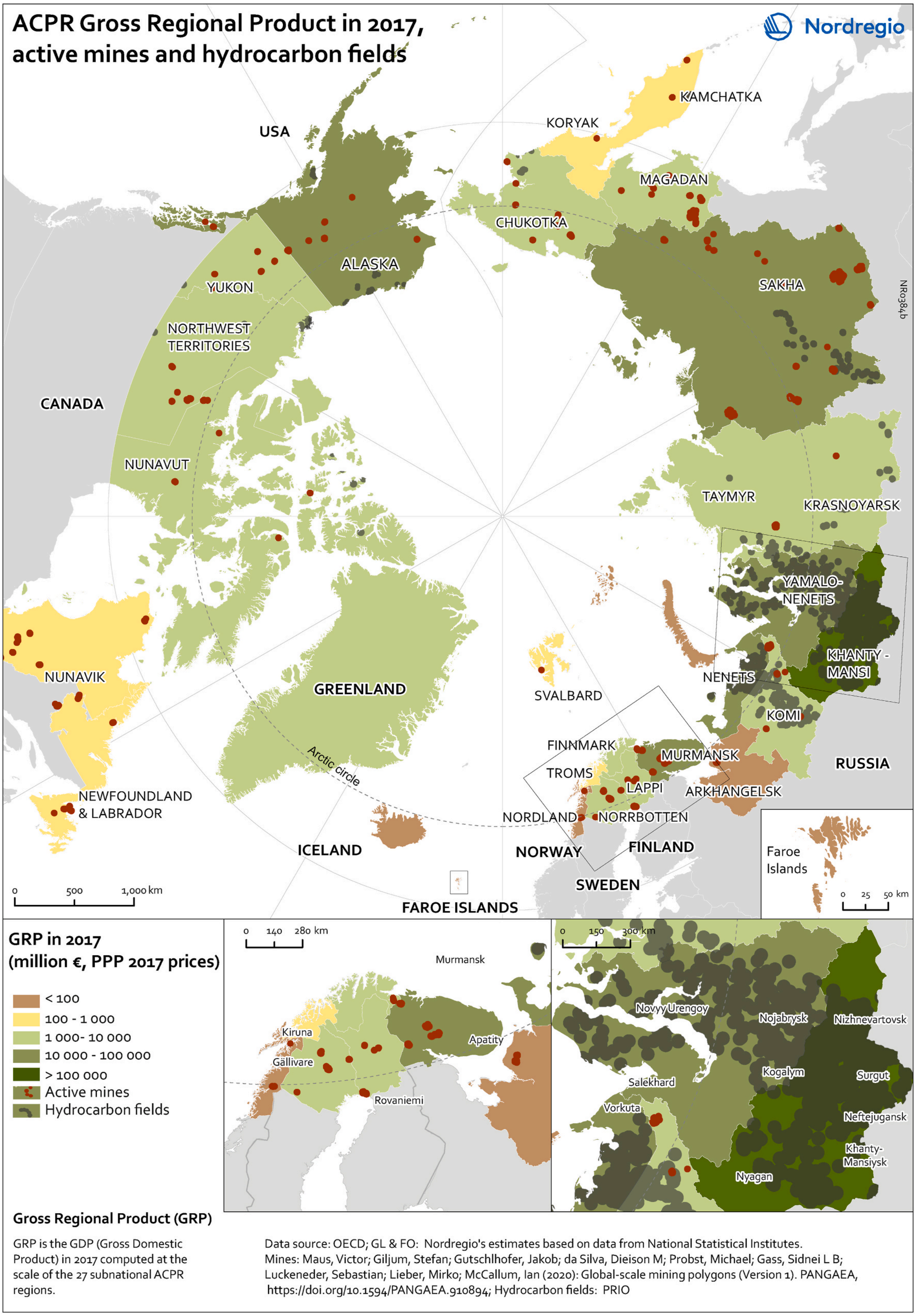

Fig. 3. Active mines, hydrocarbon fields, and GRP in the ACPR subnational regions (GRP in million € in PPP at 2017 prices). Note: hydrocarbon fields include oil and gas deposits. In addition to the 25 ACPR subnational regions, two Arctic subnational regions are also shown on the map although they are not located on permafrost: Nordland (Norway) and Faeroe islands (Denmark). Source of data used to compute the map: OECD.Stat (accessed in 2021), National statistical offices (see Ramage et al. (2021, page 26), Maus et al. (2020), and Petrodata from PRIO (Päivi et al., 2007).

Table 3
Cost of adaptation measures to overcome permafrost thaw consequences in the ACPR and maximum potential benefits that would be obtained from adaptation (that is, maximum potential avoided GRP losses). Note: € values are in billion € in PPP at 2017 prices with an annual discount rate of 3 or 4 % according to cost data sources.

ACPR countries	Total cumulative cost of adaptation measure implementation over 2022–2050	Total maximum potential cumulative benefit over 2022–2050 (maximum potential avoided GRP losses)[b]	Indicative comparison of estimated costs and maximum potential benefits (values in parentheses indicate maximum potential Net Benefit (NB) = total maximum potential cumulative benefit minus total cumulative cost)	Percentage of total cumulative cost in total maximum potential cumulative benefit (%)	Cost data sources
Russia (all ACPR subnational regions)	€ 45–190 billion	€ 1301–2966 billion	Total cost ≪ total benefit (NB ranges from € 1111 to 2921 billion)	1.52–14.60 %	Revich et al. (2022)
	€ 18–99 billion		Total cost ≪ total benefit (NB ranges from € 1202 to 2948 billion)	0.61–7.61 %	Porfiriev et al. (2019, 2021) Hjort et al. (2022)
Canada (Northwest Territories exclusively)	€ 0.025–0.044 billion	€ 27–45 billion	Total cost ≪ total benefit (NB ranges from € 26.96 to 44.98 billion)	0.09–0.16 %	Adaptative scenario: Perrin et al. (2015)
	€ 0.006–0.239 billion[a]		Total cost ≪ total benefit (NB ranges from € 26.76 to 44.99 billion)	0.01–0.89 %	Critical permafrost conditions scenario: Perrin et al. (2015)
United-States (Alaska)	€ 0.4–1.0 billion	€ 51–119 billion	Total cost ≪ total benefit (NB ranges from € 50.0 to 118.6 billion)	0.78–1.96 %	Melvin et al. (2017)

[a] This cost range in Northwest Territories (Canada) is estimated within the critical permafrost conditions scenario simulated by Perrin et al. (2015). Their results suggest that 70 % of the costs over 2022–2050 will be due to production losses due to impossible adaptation. This is because this scenario considers that for several economic activities, there will be no adaptative solutions encountered, they will just have to reduce or stop production because of unsuitable ground conditions.

[b] The total maximum potential cumulative benefits are based on our own calculations of annual GRP produced on permafrost (available in Fig. 3) summed across the 28 years over the 2022–2050 period, applying a discount rate of 3 % as in Melvin et al. (2017). This comes to assume that GRP is constant over time, which in reality is not the case.

3 % discount rate). Converted into € in PPP at the prices of the year 2017, it gives € 3.3–7.5 billion. Calculated over the period 2022–2050 for comparison with the other values displayed in Tables 3 and it gives a total cumulative cost of € 0.4–1.0 billion. The total maximum potential cumulative benefits (i.e., maximum potential avoided GRP losses in Alaska) over the 2022–2050 period that might result from adaptation measures are calculated following the same method as for the Russian Arctic (see Section 4.2.1). They are estimated between € 51 billion and 119 billion (see Table 3 for the comparison).

In the Northwest Territories in Canada, the total cost of permafrost thaw impact on roads and difficulties incurred to mine access under the RCP 8.5 global warming scenario is estimated to CAD$ 55.57 million (mean value across all model simulation results) over the period 2015–2050 (Perrin et al., 2015) with a possible variation around the mean which would give a cost range estimated to CAD$ 39.51–69.75 million (minimum and maximum value based on percentiles 20 % and 80 %, respectively). All cost from Perrin et al. (2015) mentioned in this paragraph are at prices of the year 2015 with a 4 % discount rate. Converted into € in PPP at the prices of the year 2017, it gives a mean value of € 44.02 million within a range of € 31.30–55.25 million for the minimum and maximum values. Recomputed over the period 2022–2050, for comparison with the other values in Tables 3 and it gives a mean cost of € 35.22 million within a range of € 25.04–44.20 million. This is in case of an adaptative scenario. Perrin et al. (2015) also estimated the case where the RCP 8.5 global warming scenario would generate critical permafrost conditions. In such case, total cost of permafrost thaw impact is estimated to CAD$ 213.64 million (mean value) over the period 2015–2050 with a possible variation around the mean which would give a cost range estimated to CAD$ 9.10–377.64 million. Converted into € in PPP at the prices of the year 2017, it gives a mean value of € 169.22 million (mean value) within a range of € 7.21–299.12 million for the minimum and maximum values. Recomputed over the period 2022–2050, it gives a mean cost of € 135.38 million within a range of € 5.77–239.30 million. The total maximum potential cumulative benefits (i.e., maximum potential avoided GRP losses in the Northwest Territories in Canada) over the 2022–2050 period that might result from adaptation measures are calculated following the same method as for the Russian Arctic (see Section 4.2.1). They are estimated between € 27 billion and 45 billion (see Table 3 for the comparison).

It should be noted that the costs of adaptation measures to overcome permafrost thaw consequences are derived from multiple studies published by various authors (as cited in Sections 4.2.1 and 4.2.2). Consequently, these estimates are not directly comparable across ACPR countries due to differences in estimation methodologies.

5. Discussion

With thawing permafrost, economic activities and infrastructure assets (e.g., harbours, industrial and urban infrastructure, equipment, mines, oil fields, etc.) are at risk of damages with consequences for local inhabitants. Domestic and foreign investors might lose income when economic activities decline or shut down. There are also consequences for national governments' budgets due to tax losses (corporate taxes and personal income taxes).

Calculating the GRP produced on permafrost in the ACPR (Sections 3 and 4) is one way to assess the importance of economic activities on permafrost highlighting the need to preserve this economic value from the adverse effects of permafrost thaw. However, the total GRP produced on permafrost in the ACPR (€ 84–189 billion in 2017, see Section 4) is not necessarily at risk. Only a portion of this total will decrease as permafrost thaws. Further studies should estimate that portion, for example, by applying a model predicting permafrost thaw on top of our permafrost GRP estimations (Figs. 2 and 3). Further studies should also complete our permafrost GRP estimations since we did not include informal economic activities – e.g., hunting, fishing, and gathering practices for food provision – that is essential for indigenous people living in the Arctic (Ramage et al., 2022). In that sense, using GRP as an indicator leads us to underestimate the impact of permafrost thaw on economic activities.

Another limitation of our study is the lack of differentiation in thaw sensitivity based on excess ground ice content. In permafrost soils, excess ice occurs when the ice content exceeds soil porosity, forming ice lenses and wedges (Lee et al., 2014). The volume of excess ice influences the extent of ground deformation and infrastructure damage caused by permafrost thaw. As explained by O'Neill et al. (2020), thawing ice-rich permafrost affects soil moisture availability, topographic adjustments (e.g., surface subsidence and ponding), and the thermal response of the ground to warming. The melting of excess ice not only increases moisture in the active layer but also delays thaw penetration into the ground due to latent heat effects. Similarly, Lee et al. (2014) show that including excess ice in permafrost models delays thaw by approximately 10 years at 3 m depth in areas with high excess ice content. Furthermore, the thaw of ice-rich permafrost can lead to the collapse of land surfaces previously supported by ice wedges and lenses, resulting in land surface subsidence (Lee et al., 2014). These processes have direct implications for infrastructure stability and economic assessments. Our study does not account for differences in thaw sensitivity due to varying excess ground ice content. Future research in permafrost economics should incorporate spatially explicit excess ice data to refine economic vulnerability assessments and improve projections of permafrost-related infrastructure damage.

An important limitation in our approach, as recommended by one of the anonymous reviewers, should be noted: estimating the GRP of individual settlements by multiplying the population by the regional average per capita GRP may not capture significant intraregional economic disparities, particularly in regions with specialized industries, such as hydrocarbon production in northern Russia. For example, in the region Yamalo-Nenets Autonomous Okrug, two settlements of similar population size might have vastly different economic profiles—one heavily engaged in hydrocarbon production, while the other relies primarily on non-market services. Our methodology would yield similar GRP estimates for both, which may overlook these critical local economic distinctions. Therefore, our results are not suitable for assessing economic vulnerabilities to permafrost thaw at the local level or for evaluating individual settlements. Instead, they are intended to provide insights at regional and national levels across the 25 regions within the eight Arctic countries.

Another drawback of our assessment of the threats posed by permafrost thaw is we primarily based the calculation on the presence and extent of permafrost itself. However, the level of damage experienced in a particular settlement or region is contingent upon the expertise of planners, designers, and infrastructure managers. Consequently, significant variations can arise between regions with similar permafrost conditions. These factors are not incorporated into our calculations. Information on these factors is often limited, complicating their inclusion. This may have resulted in an underestimation of the GRP at risk in ACPR regions characterized by limited expertise or financial resources to address permafrost thaw, while simultaneously leading to an overestimation of the risk in areas equipped with higher levels of expertise and financial capacity.

An additional consideration in our study is that some of the economic studies we relied on to estimate adaptation costs to permafrost thaw also account for damages resulting from general climate warming (which includes permafrost thaw) rather than isolating the specific impacts of permafrost thaw. For instance, Perrin et al. (2015) assessed adaptation costs in Canada, which encompassed the increased construction and maintenance of ice roads (such as those that traverse frozen lake surfaces in Northern Canada) as well as overland routes, known as portages, which follow low-lying terrain, including frozen streams and wetland areas near lakes. This broader scope may have led us to an overestimation of adaptation costs directly related to permafrost thaw.

Our results show that the regions with the highest GRP on permafrost (Yamalo Nenets, Sakha Republic, and Khanty-Mansi Autonomous Okrug), are also those with the highest number of active mines and hydrocarbon fields (Fig. 3). If ground conditions around active mines and hydrocarbon fields under future permafrost thaw make the access by roads difficult, it may adversely impact mining, oil and gas extraction activities, reducing drastically the GRP produced in those regions. The same in case oil and natural gas transportation become increasingly difficult due to pipeline collapse and expensive repair and maintenance operations. The impact on the rest of the world may also be significant in case reduced production due to degraded ground conditions would lead to reduced oil and gas exportations from Arctic regions. Following the law of supply and demand in economics, it might lead to an increase in fossil fuel prices on international markets due to a drastic reduction of supply. We should also mention that as permafrost thaws, the number of settlements on permafrost will shrink drastically, which will automatically lead to a shrinking of the GRP.

Our results displayed on Fig. 2 show that Russia is prevailing in the ACPR economy. About 91–92 % of the total GRP at risk in the ACPR is produced on the Russian territory (permafrost GRP in Russia: €76–174 billion; total permafrost GRP in the ACPR: €84–189 billion). This means many countries depending on Russian ACPR exports will be in troubles in case of reduced economic production due to permafrost thaw, as already illustrated by the current reduction in Russian exports due to the armed conflict between Russia and Ukraine. Fig. 3 shows that in the ACPR, mining activities, oil and natural gas extraction are mainly located in Russia. Countries which relied the most on fossil fuel exports from Russia before the armed conflict will be directly impacted in case of permafrost thaw and assuming Russian exports will start again after the armed conflict ends. The most concerned countries will be Lithuania (before the armed conflict, 97.7 % of its domestic fuel consumption in the total oil, coal and natural gas supply came from Russian imports), Slovakia (59.9 %), Netherlands (54.8 %), Hungary (54.3 %), Greece (53.0 %), Finland (44.6 %), Bulgaria (40.4 %), Poland (37.2 %), Latvia (30.5 %), Germany (28.3 %), Belgium (28.6 %), Italy (25.1 %), Czech Republic (23.7 %), and Turkey (22.1 %) – percentages are from IEA (2022) for the year 2020. Fossil fuel supply reductions can generate tremendous price increases as already observed worldwide in 2022 due to the end of Covid-19 sanitary measures. The post-lockdown energy demand exceeded supply, and the Russia-Ukraine war intensified the gap between demand and supply by its impact on supply chains that reduced the availability of fossil fuels in Europe.

Given these potential consequences, implementing adaptation measures to permafrost thaw should be considered. However, adaptation measures are expensive. This raises an important question: should adaptation be viewed as an economic gain or as a cost? To address this, in Section 4.2, we estimate the maximum potential economic production – based on GRP values estimated in Section 4.1 – that could be preserved if adaptive measures are taken to counter the effects of permafrost thaw under the IPCC RCP 8.5 global warming scenario (IPCC et al., 2014, p. 179). The results show that in all subnational regions studied in Table 3, the total cumulative implementation costs of adaptation measures aimed at overcoming permafrost thaw are much lower than the total maximum potential cumulative benefits that could result from these measures. This suggests that both public authorities and the private sector should further investigate whether implementing such adaptation measures in the ACPR would indeed result in net economic benefits. However, it is important to acknowledge that our analysis does not constitute a formal cost-benefit analysis, as the estimated benefits are indicative rather than definitive. These estimates represent an upper bound of potential avoided economic losses, not precise economic valuations. Therefore, the maximum potential benefits presented should be interpreted as suggestive rather than conclusive economic figures.

However, it is important to acknowledge a significant limitation in our assessment of adaptation costs in Russia. Due to a lack of available studies and data specific to Russia, the adaptation costs we referenced from previous research are confined to residential buildings, healthcare facilities, and roads, omitting railways, pipelines, airports, and mine access. As a result, we were unable to address adaptation measures within key industrial sectors in the Russian North. This limitation suggests that our analysis may not fully capture the adaptation costs associated with permafrost thaw for industries critical to the GRP in Northern Russia. Future studies that incorporate adaptation measures across a broader range of sectors could provide a more comprehensive understanding of the economic implications of permafrost thaw. However, it should be noted that, to date, no studies of this nature – encompassing all subnational regions within the Russian ACPR – have been conducted or are available in English (we have not reviewed Russian-language scientific literature).

The choice of a 3 % discount rate for projecting adaptation costs through 2050 warrants further discussion and potential reconsideration, particularly in light of Russia's current context of elevated economic uncertainty and geopolitical instability (e.g., the ongoing conflict with Ukraine). This heightened risk environment suggests that using Russian government bond yields, rather than discount rates based on literature focused on permafrost thaw and climate impacts in North America, could better capture the economic impacts of permafrost thaw in Northern Russia. For example, the current yield on Russia's 10-year government bond stands at 16.726 % (which is quite high), reflecting the return investors expect for holding the bond to maturity and indicating substantial economic uncertainty and perceived risk. Higher bond yields generally signal greater risk and instability in the economic outlook. Adopting a discount rate based on these yields could provide a more accurate assessment of the economic implications of permafrost thaw, better aligned with Russia's economic realities and the anticipated risks and uncertainty in the coming decades.

The temporal limitations of our analysis represent a critical consideration in interpreting our findings. Our analysis is based on economic data from 2017. And yet, two significant global events since then may have impacted the relevance of our estimates. The COVID-19 pandemic and the war in Ukraine have led to significant changes in the economy globally, and particularly in Russia (in the context of the war). Covid-19 has generated structural changes in the economy wordlwide, such as increasing economic inequatily between different economic groups, digital transformation as many businesses were forced to shift to digital platforms (creating a technological divide between large companies who can adapt and small businesses who cannot), business closures and workforce reductions have increased unemployment rates, changes in work patterns with many jobs shifting to remote work, which might have changed labour productivity and as such GRP growth rates (Oktapela and Damayanti, 2024). These transformations have reshaped the economic landscape by driving faster automation and digitalization (Oktapela and Damayanti, 2024). The COVID-19 pandemic has profoundly and extensively altered economic structures. These changes are not merely temporary but generate a shift in economic and social structures and have long-term implications for global and national economies (Oktapela and Damayanti, 2024). According to a World Bank report by Guenette et al. (2022), the war in Ukraine is affecting commodity markets, trade, and financial flows at global scale. The war shocks caused considerable effects on macroeconomic conditions, global financial stability, and generated a decline in GDPs of many countries (compared to GDP levels that would have been achieved without the war) as well as an increase in inflation, which reflect the war's nature as a contractionary supply shock (Tong, 2024). As explained by Guenette et al. (2022), the war in Ukraine has significantly reduced global economic growth prospects in the short term. Prices for commodities supplied by Russia and Ukraine (that is, energy, wheat, fertilizers, and some metals) are higher since the war started. In many countries, rising food and energy prices are increasing poverty and rising inflation pressures. The war has weakened global economic growth, increased food insecurity as well as financing costs and the risk of financial crises. Guenette et al. (2022) also explain that the war is contributing to the fragmentation of global trade and foreign investment networks. Liadze et al. (2023) estimated the economic cost of the first year of the Ukraine war on the global economy to 1 % of global GDP in 2022 (that is, a 1 % GDP loss compared with GDP forecast in a business as usual scenario without war). Europe is the most affected region, given its trade links, proximity to Ukraine and Russia, and reliance on energy and food supplies from those countries (Liadze et al., 2023). Both, post-Covid effects and the Ukraine war may have changed GRP per capita values among the subnational regions in the ACPR and generated permanent long-run shift of future GRP trends. Therefore, it is important to consider that the results presented in this paper may be influenced by outdated economic data, as such they are only indicative and should be confirmed by further studies.

6. Conclusion

The Gross Regional Product (GRP), defined as the Gross Domestic Product (GDP) estimated at sub-national levels, produced on permafrost in the ACPR ranges between € 84 billion and € 189 billion in 2017 (Section 4). Disaggregated per Arctic countries, the GRP produced on permafrost is of €76–174 billion in Russia, €3–7 billion in the United-States (Alaska), €4–6 billion in Canada, €0.7–1.4 billion in Denmark (Greenland), €0.09–0.6 billion in Sweden, €0.1–0.4 in Norway, €0.002–0.3 billion in Finland, and €0.00–0.01 billion in Iceland (Fig. 2). Russia is prevailing in the ACPR economy. About 91–92 % of the total GRP at risk in the ACPR is produced on the Russian territory (permafrost GRP in Russia: €76–174 billion; total permafrost GRP in the ACPR: €84–189 billion). This means many countries depending on Russian ACPR exports will be in troubles in case of reduced economic production due to permafrost thaw, as already illustrated by the current reduction in Russian exports due to the armed conflict between Russia and Ukraine.

To avoid economic disruptions at subnational, national, and international levels, national governments, and subnational public authorities in the ACPR countries should be willing to pay at least a certain percentage of the total permafrost GRP to reduce the impact of permafrost thaw on their resource-based industries. What percentage would be politically acceptable? This is a question that should be democratically negotiated by decision-makers. However, Table 3 (in penultimate column) shows that the cost of adaptation to permafrost thaw in the ACPR is between 0.01 % and 14.6 % of the GRP produced on permafrost. A certain proportion of this permafrost GRP will be lost in the coming decades. Is it worth to spend 0.01–14.60 % of the permafrost GRP in adaptation costs to avoids such a loss? This means that for adaptation measures to become economically and politically interesting for the governments of ACPR countries, GRP losses due to permafrost thaw (estimated in a future without adaptation measures) should be higher than this percentage range. This would be an incentive for the governments to undertake actions to avoid permafrost GRP losses. To answer that question, further research is still needed to couple our permafrost GRP maps with permafrost thaw modeling and precisely assess the portion of permafrost GRP that will be effectively shrinking in the next decades because of permafrost cover decrease.

Further research is also needed to reduce the range of our estimations and to improve their accuracy. Physical science could help to progress in that direction since economic evaluations of climate change impacts always rely on physical basis estimations. For example, this would require producing maps with narrower range of permafrost categories showing the exact percentage of the territory that is covered by permafrost types (not wide ranges of values as it is currently the case). There is also quite some work done by Russian scientists for example on assessing the exact location of permafrost thaw along pipelines. Scientists do that for private industries and oil companies as it is a part of their eco-monitoring and preconstruction duties. There is an urgent need to make these data publicly available and, if possible, translate them into English otherwise it is hard to reach for non-Russian scientists.

The estimates we provide in this paper are based on economic data from 2017, before the COVID-19 pandemic and the war in Ukraine. These two global disruptions have changed the economy worldwide, especially in Russia due to its military involvement in the war. As a result, they may have caused permanent long-term shifts in potential GDP and GRPs in Russia and possibly in other ACPR countries. Therefore, our results should be interpreted with caution. Future research should update these estimates with more recent data to capture the post-covid and post-Ukraine war economic landscape. This would help improve the robustness of our results.

CRediT authorship contribution statement

Mateo Cordier: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anna Vasilevskaya:** Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Leneisja Jungsberg:** Writing – review & editing, Validation, Project administration, Formal analysis, Conceptualization. **Jean-Paul Vanderlinden:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Justine Ramage:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Hugues Lantuit:** Writing – review & editing, Validation, Project administration, Funding acquisition.

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Declaration of competing interest

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Appendix A. Supplementary data

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