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Review

Risks for Public Health and Social Infrastructure in Russian Arctic under Climate Change and Permafrost Degradation

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Abstract: This study analyzes the risks to public health and life quality in the conditions of permafrost degradation caused by the ongoing climate change in the Russian Arctic. There are more than 200 Siberian anthrax cattle burial grounds in the Russian permafrost regions. Permafrost degradation poses the risks of thawing of frozen carcasses of the infected animals and propagation of infectious diseases. Permafrost degradation leads to infiltration of toxic waste in the environment. Such waste contains mercury, which migrates into the rivers and forms methylmercury (MeHg) in fish. Other risks associated with permafrost degradation include damage to the existing social infrastructure (housing, health-care facilities, roads, etc.). Various risks to public well-being that emerge because of permafrost degradation were addressed in this study. Relative hazard indices were developed and calculated to characterize the probability of outbreaks of Siberian anthrax in the future. These indices linked the rates of permafrost degradation and the number of Siberian anthrax cattle burials to the potential hazard of re-emergence of Siberian anthrax among local populations in 70 municipal districts under the ongoing warming. The expected damage to public housing, health-care facilities, and motorways was assessed. Accessibility of health care in various regions of the Russian Arctic was analyzed. The economic costs associated with various scenarios of possible destruction of residential buildings, health-care facilities, and roads built on permafrost were estimated.

Keywords: public health-care; infectious diseases; Siberian anthrax; tick-borne encephalitis; toxic metals; mercury; nickel; lead; stability of buildings

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1. Introduction

The rate of climate warming in the Arctic is greater than elsewhere in the Russian Federation. This rate is approximately twice as much as the world's average, as was shown by the linearization of the trends in annual average temperatures of the North Polar Region over the past 40 years (1976–2018) [1].

Further warming will lead to even faster degradation of the permafrost layer [2]. According to the IPCC, it will lead to a 90% reduction of permafrost area by 2100, and even faster degradation will happen with 20% of this area [3]. The rate of permafrost degradation will depend upon local conditions and greenhouse gas emission dynamics.

An extensive network of 250 weather stations monitors ground-level air temperatures in the North Polar Region. The annual average temperatures increase, with the greatest rates along the coast of the Arctic Ocean, especially in Siberia (between +0.8 °C/10 years and +1.2 °C/10 years in the Taymyr Peninsula and the East Siberian Sea). The largest temperature anomalies have been observed in East Siberia and West Siberia. The spatially averaged values of mean annual temperature anomalies in these regions reached 5.9 and 3.7 °C, respectively [4]. Since 2007, annual average ground-level temperatures have increased by 2.8 °C in East Siberia and Yakutia [5]; this caused an increase in the temperatures of the upper permafrost layer by 0.4–1.3 °C [6]. Annual average temperatures in West Siberia grew at the rate of 4.0–5.5 °C/100 years [7]. Figure 1 presents the results of monitoring of correlations between the rates of increase in annual average air temperatures and permafrost degradation.

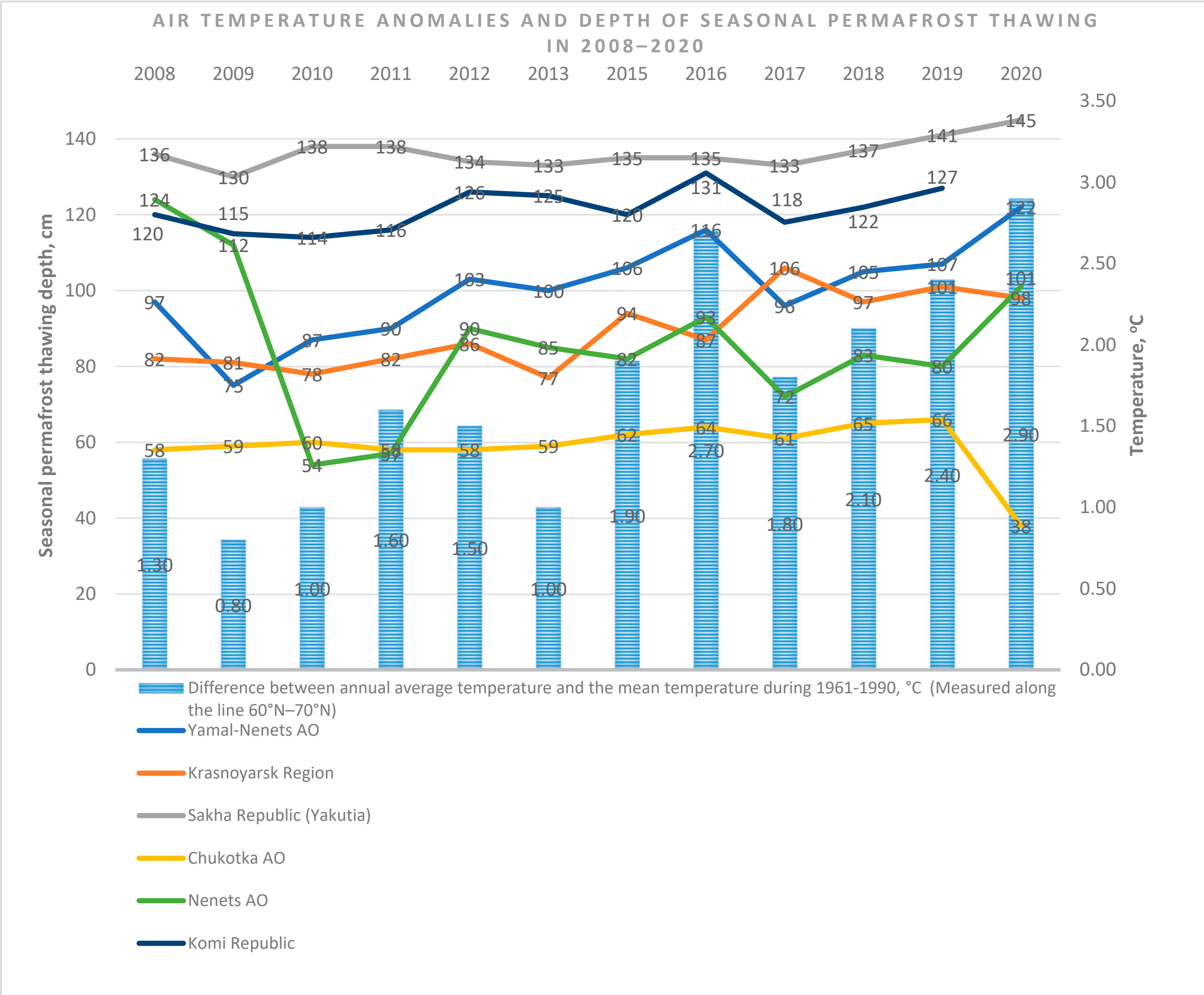

Figure 1. Air temperature anomalies and depth of seasonal permafrost thawing in 2008–2020. Seasonal thawing depths were averaged by region based on the data reported by the Circumpolar Active Layer Monitoring (CALM) program. Available online: https://www2.gwu.edu/~calm/data/north.htm (accessed on 21 March 2022). Incomplete time series from several monitoring stations were excluded. AO—Autonomous Oblast (Region). Source: Authors' calculations.

The collected data largely confirmed the correlations between air temperature anomalies and the depth of active permafrost layer. Gradual rise in ground-level air temperatures leads to increase in the depth of the active layer every year.

The existing projections of future temperature trends depend upon the region and greenhouse gas (GHG) emission pathways. Under the moderate global warming scenario RCP4.5, average summer temperatures will rise by 3.0 °C in Archangelsk and by 2.0 °C in Yakutsk by the end of the 21st Century, with respect to the baseline values of 1990–1999. The same estimates under the RCP8.5 scenario are 5.0 °C in Archangelsk and 3.3 °C in Yakutsk [8]. It is predicted that permafrost degradation will directly affect 3.6 million residents of the Arctic region by the year 2050 [9]. Even today, negative consequences are clearly seen. Soil temperatures increase as the summer air temperatures rise, causing permafrost degradation. Temperature measurements in West Siberia showed that climate change was associated with increases in soil temperatures and permafrost temperatures at varying depths [10].

In Russia, the processes of permafrost degradation are most pronounced in Nenets Autonomous Oblast (AO), North Urals, West Siberia, Yamal Peninsula, and a major part of East Siberia: Krasnoyarsk region, Sakha Republic (Yakutia), Chukotka, and Kamchatka. For example, permafrost soil temperatures measured at 1.6 m depth have already increased by 0.1–1.2 °C above the norm [11]. A 2 °C increase in the mean global temperature will lead to complete thawing of 15–20% of Arctic permafrost areas [9]; some other researchers predicted even greater loss [12].

The consequences of climate change to public health in the Russian Arctic will be quite diverse, including the following: an increase in the number of heat waves will lead to excess mortality among urban populations, as reported in our previous research [8,13–15]; traditional lifestyles of the indigenous peoples of the North will be disrupted [16]. A survey of Central Yakutia residents identified their concerns about the ongoing changes in the landscapes and weather in 2006–2016. The residents indicated that they experienced problems with accessibility of medical services and shopping; the foundations of their houses were crumbling, which was considered a direct consequence of warmer winters; and there was loss of reliable ice crossings that they used for transportation [17]. This paper considers the following risks to public health caused by permafrost degradation: re-emergence of outbreaks of Siberian anthrax, and, possibly, other infections, as a result of thawing of cattle burial sites; development of infections caused by changes in vegetation (northward propagation of taiga); destruction of engineered infrastructure, including hospitals, residential houses, and roads; possible infectious contamination of foods used by the indigenous peoples of the North, as a result of thawing of glaciers; risks to deer breeding, such as injuries of the deer caused by permafrost thawing; possible destruction of shoreline constructions caused by coastal abrasion; and other types of risks.

2. Materials and Methods

Relative hazard indices were developed to link the rates of permafrost degradation, the number of Siberian anthrax cattle burial sites, and population density to the potential hazard of outbreaks of this disease among local populations. Two hazard indices were calculated for each administrative district within the Russian Arctic cryolite zone, where the Siberian anthrax cattle burials were present: territorial hazard HI_{terr} and population hazard HI_{pop}. Although the probabilities of potential outbreaks cannot be calculated at this stage, in our opinion, they must be proportional to the developed indices.

The territorial index characterized the probability of potential outbreaks of Siberian anthrax among cattle, while the population index characterized the probability of potential outbreak among the population of this district. The absolute values of the developed indices are not essential, but the districts can be compared and ranked according to these indices. The greater the index, the higher the probability of the outbreak.

HI_{terr} is the product of the two values: (1) the number of the disease agents that are present in the active layer in cryptobiotic state, which is proportional to the number of stationary unfavorable sites N within this territory, and (2) the permafrost degradation rate. This rate is proportional to the increment of temperature within the active layer in the summer season ΔT_{cryo} between two 30-year periods: 1960–1989 and 1990–2019. We assumed that the seasonal permafrost thawing would trigger activation of the disease agents. HI_{terr} was calculated as follows:

$$HI_{terr} = N \times \Delta T_{cryo};$$

$$\Delta T_{cryo} = \Delta T_{air} \times k,$$

where ΔT_{air} is the change in the mean summer temperatures (June–August) between 1960–1989 and 1990–2019, and k is sensitivity of perennial permafrost to the changes in air temperatures.

Temperature measurements were retrieved for the nearest weather station from the network of 518 Roshydromet (Russian Hydrometeorology Service) stations [18]. The coefficient k is the ratio of the change in cryolithozone temperature at a 10 m depth and the change in the ground-level air temperature. The seasonal variations in cryolithozone temperature are negligible at this depth [19]. The recommended normative depth of Siberian anthrax cattle burial or a 'biothermal pit' is also 10 m [20]. Actual depths could vary between 2 and 10 m; the shallowest are the plague pits and trenches. The values of coefficient k that characterizes the sensitivity of the active layer to the changes in air temperatures varied between 0.3 and 0.8, and were derived by spatial interpolation from the map presented in [21].

The population hazard index HI_{pop} was the product of HI_{terr} and the population density within the corresponding administrative district. Thus, we assumed that the influence of the neighboring districts on the population risk was negligible.

All administrative districts were ranked according to the obtained HI_{terr} and HI_{pop} values. Based on the calculated indices, the authors also proposed two discrete (categorical) hazard scales graded from 1 (low) to 6 (extremely high) risk. The scores ranging from 1 to 6 were assigned to each district because they are easier to interpret for the characterization of relative hazard.

The analysis of the distribution of the estimated HI_{terr} values indicated an outlier in Srednekolymsky District of Yakutia (21.26). The remaining values varied within the interval between 0.17 and 13.24. These two values differ by less than two orders of magnitude. The scores were assigned linearly after dividing this interval into six equal bins numbered 1 to 6; the width of each bin was equal to $(13.24 - 0.17)/6 = 2.18$; then score i was assigned to all HI_{terr} values within the interval $(0.17 + (i - 1) \times 2.18; 0.17 + i \times 2.18)$.

The scores of population hazard were calculated on a logarithmic scale, because the underlying distribution of the HI_{pop} values had a (nearly) exponential character, with the outliers in the compact urban municipal districts. The HI_{pop} values differed by five orders of magnitude, between 0.02 in Khatangsky District and 6747.26 in Naryan-Mar urban district. The population hazard score S was calculated as the integer part of $(1 + \lg(HI/HI_{\min}))$.

Thus, $S = 1$ was assigned to $0.02 \leq HI_{pop} < 0.2$, $S = 2$ was assigned to $0.2 \leq HI_{pop} < 2$, and so forth. The districts with $S = 2$ are approximately 10 times more hazardous than the districts with $S = 1$, the districts with $S = 3$ are approximately hundred times more hazardous than the districts with $S = 1$, and so forth. The logarithmic scales of relative hazards have been widely used in science and engineering, as they meet our intuitive perception of hazard by the intensity of its impacts, for example, the Mercalli seismic intensity scale.

Availability, and accessibility, of health-care services in the Russian Arctic is seen as a source of social inequality among the dispersed populations scattered across large areas, which makes Arctic residents especially vulnerable to health risks. A map of transport accessibility of medical services in Nenets AO and Archangelsk Oblast was developed using Euclidean metrics and the Thiessen–Voronoi polygons; the automobile road density was measured within each polygon [22].

The economic losses due to destruction of infrastructure objects in the conditions of permafrost degradation were estimated in [23,24] with a spatial model that linked the permafrost degradation rates to the associated infrastructure maintenance costs. Various infrastructure objects were counted and geopositioned on the permafrost distribution map. The authors used the data on the areas of the residential buildings and health-care facilities and the total length of automobile roads. Geopositioning of the objects of several types involved a synthetic localization technique based on the International Permafrost Association data. With respect to permafrost prevalence, four types of areas were identified: (1) continuous, (2) intermittent, (3) fragmentary, and (4) sporadic permafrost. These types denoted the regions where permafrost covered, respectively, 100–90%, 90–50%, 50–10%, or less than 10% of the territory. The rock-ice content was graded as high, medium, and low. The authors then assumed that 90% of all buildings were built on permafrost in the regions of continuous permafrost, 50% of all buildings were built on permafrost in the 'intermittent permafrost' regions, 10% of all buildings were built on permafrost in the 'fragmentary permafrost' regions, and there were no structures built on permafrost in 'sporadic permafrost' regions.

The model assumption about the fractions (90%, 50%, 10%) have been verified using the test samples of geopositioned buildings and seems plausible from the construction cost minimization standpoint. Each permafrost region has certain areas where permafrost is absent due to specific physical and geological conditions (e.g., outcrops of solid rocks). These permafrost-free areas are used for the construction of the infrastructure objects to achieve cost savings. Examples include the permafrost regions of Murmansk Oblast, Perm Oblast, and the South Urals highlands. There is no need to build on permafrost because of the sluggish regional economies and availability of permafrost-free areas.

The stability of infrastructure objects means a continuous and stable use of these objects within the normal cycles of economic activity. Permafrost degradation poses the risks of destruction of the buildings' foundations, which ultimately lead to destruction of the whole building so that it needs to be replaced or reconstructed.

Economic valuation of engineered structures including buildings involved the normative or actual prices and construction costs depending upon data availability.

The final stage of economic assessment involved geopositioning of the buildings and other infrastructure objects within the spatial model that predicted the dynamics of permafrost thawing in the future. The extent and the depth of permafrost thawing were predicted until the year 2050 in the conditions of climate change under the RCP8.5 global warming scenario. Presently, Volume 1 of the IPCC Sixth Assessment Report (AR) has been published. This report considers permafrost degradation as a key issue in the context of climate change. The estimates presented in the Sixth AR correspond to the results of our economic valuation model, because our model was based on the most representative scenario of climate changes in the Arctic macroregion. Besides, a draft of the second volume of the Sixth AR (2022) included the projections of economic damage due to permafrost degradation published in our earlier work [24]. Several sources cited in the Sixth AR mentioned the acceleration of the processes of permafrost degradation.

Economic costs were estimated in rubles and then converted to US dollars using the purchase parity coefficient calculated by a standard OECD method (1 USD = 24.5 RUR). This conversion factor is clearly less than the official exchange rate but more realistic.

A detailed methodology of the economic assessment of damage to various sectors of the economy due to permafrost degradation can be found in [22–25]. The basic equation for cost assessment contains the following variables: the unit costs of restoration of the destroyed infrastructure objects of different types, total damage in natural units (the area of the buildings or the length of the roads), and the climatic coefficient calculated from the climatic geotechnical model (Table 3 in [24]). For the unique objects, we used the data on the extent of permafrost degradation from the CALM model https://www2.gwu.edu/~calm/data/north.htm (accessed on 21 March 2022), with corrections for the ice-rock content [25,26].

3. Results

3.1. Global Warming, Permafrost Degradation, and Infectious Diseases

There are indications that global warming leads to permafrost degradation, and this may facilitate the possible release of various microorganisms including pathogens. Recent research showed that prokaryote and eukaryote bacteria might remain viable in the conditions of year-round negative temperatures of permafrost soils that are from several thousand to 2–3 million years old. Viable cysts of Paleolithic bacteria have been identified that had been in a cryptobiosis state for several hundred thousand years. This finding confirmed a possibility of reactivation of vectors of infectious diseases that remained frozen in permafrost for a very long time and can be released in the environment as a result of climate changes [27]. Research findings indicate that viable viruses may survive in the tissues of people killed by smallpox that are buried in permafrost. This finding was also supported in a study of virus strains that were stored in the national collection for 26 years and survived. The authors of the study calculated that infectious material in tissues may survive under negative temperatures for up to 250 years. The study of samples of the naturally frozen brain of a Yukagir mammoth, estimated to be over 18,000 years old, identified a high concentration of at least seven morphotypes of viable thermotolerant aerobic bacteria, with unstable characteristics permitting to relate to new species, which could become pathogens for humans [28,29]. The microbiologic analysis of the soft tissues of six mammoths, the Kolyma woolly rhinoceros, the Omoloy calf, and the Yukaghir horse and bison, identified 42 strains of the *Bacillus* bacteria [30].

The part of West Siberia beyond the Polar Circle was plagued by Siberian anthrax in the past; more than 70 large outbreaks have happened there since 1760. Such outbreaks typically occurred in the summer when the deer contracted this disease from the contaminated soils. The outbreaks became less common after a massive vaccination of domestic animals in the 1940s. There were several registered cases of Siberian anthrax among people in 1931 and 1941. After a long period of sanitary well-being without the outbreaks, the total vaccination of deer was abolished in 2007. An extremely hot summer of 2016 caused a 2 meters' deep seasonal thawing of permafrost and, possibly, vegetation of Siberian anthrax bacteria, its migration from the active permafrost layer to the surface soil, and a consequent large-scale outbreak of Siberian anthrax among deer. Permafrost degradation may lead to migration of these bacteria to the surface with groundwater.

There are between 300 and 500 Siberian anthrax cattle burial grounds in the Russian Arctic, according to various literature sources. Such sites are mostly located in Nenets AO, Archangelsk Oblast, Komi Republic, and Yakutia [31]. The authors of this survey predicted a possible outbreak of this disease in Russian permafrost regions in an earlier paper published in 2011 [32], and it indeed happened in 2016 in the Yamal Peninsula (West Siberia) [33,34]. A possible cause of the outbreak was the anomalous heat wave mentioned above.

The goal of our later study was to conduct a spatial assessment (zoning) of the Russian permafrost belt with respect to possible risk of future outbreaks of Siberian anthrax as a result of thawing of the frozen soil with the reindeer carcasses buried in it infected with anthrax decades ago. For each municipal district of the Russian Arctic where permafrost was present, the authors developed two hazard quotients, which measured the relative hazard of being infected for the deer (territorial hazard) and for the people (population hazard). Both indicators can be important for decision makers. The maximum value of the 'territorial hazard' index was estimated for Srendekolymski District in Yakutia [18]. Table 1 ranks the municipal districts of the Russian Arctic according to the estimated relative hazard of outbreaks of Siberian anthrax among cattle (using the territorial hazard index) and people (using the population hazard index). Table 1 also groups the municipal districts into the six relative hazard classes ranging from 1 (low) to 6 (extremely high).

Another study was conducted in Yakutia to estimate the risk of contamination of the environment by 'paleobiologic waste' (i.e., the resurfaced carcasses of the diseased animals) as a result of permafrost degradation. The authors used a geometric stratification technique and confirmed that the highest risk could be expected in the Yamal Peninsula and the northeast districts of Yakutia [35], where 739 historic outbreaks of Siberian anthrax were recorded between the years 1811 and 2018. During this period for which sanitary records were available, about 80,000 animals (mainly deer and horses) died from this disease [36]. Permafrost is present not only in the Russian Arctic territories but also in Siberia and Far East regions. For this reason, the sanitary surveillance of Siberian anthrax cattle burials has been reinforced and strengthened in the conditions of ongoing climate change. The boundaries of sanitary protection zones have been specified and updated, and modern methods of sanitary monitoring have been developed for permafrost territories [37].

Table 1. Ranking of municipal districts by relative hazard of outbreaks of Siberian anthrax among cattle (using the territorial hazard index) and people (using the population hazard index).

Hazard for Cattle				Hazard for People		
Subject of RF	**Municipal District**	HI_{terr}	**Score**	**Municipal District**	HI_{pop}	**Score**
Yak-Arctic	Srednekolymsky	21.26	6	Naryan-Mar u.o.	6747.26	6
Yak-West	Mirninsky	13.24	6	Syktyvkar u.o.	436.8	5
Yak-West	Niurbinsky	12.45	6	Yakutsk u.o.	357.38	5
NAO	Naryan-Mar u.o.	12.32	6	Lesosibirsk u.o.	75.85	4
Taymyr	Dudinka u.o.	11.36	6	Chusovskoy u.o.	17.71	3
Taymyr	Ust-Yeniseisky	9.54	5	Ukhta u.o.	17.46	3
Yak-East	Oimyakonsky	9.13	5	Namsky	14.75	3
Chukotka	Chukotka AO	9.08	5	Ust-Aldansky	9.98	3
Yak-Centre	Ust-Aldansky	8.76	4	Sosnogorsky	6.78	3
Yak-Centre	Amginsky	8.2	4	Mirninsky	5.76	3
Yak-West	Viluisky	8.19	4	Niurbinsky	5.69	3
KHMAO	Khanty-Mansiisky	8.07	4	Churapchinsky	5.53	3
Koryak	Koryak AO	8.02	4	Khangalassky	5.22	3
Evenk	Evenk AO	7.61	4	Amginsky	4.66	3
Yak-Centre	Gorny	7.45	4	Minusinsky	4.4	3
Magadan	Magadan Oblast	7.16	4	Viluisky	3.71	3
Yak-Centre	Namsky	7.12	4	Khanty-Mansiisky	3.51	3
Yak-West	Verkhneviluisky	6.82	4	Verkhneviluisky	3.41	3
Yak-Centre	Kobyaisky	6.82	4	Kudymkarsky	3.21	3
Yak-Arctic	Oleneksky	6.13	3	Abansky	3.06	3
Yak-South	Olekminsky	4.96	3	Syktyvdinsky	2.69	3
YANAO	Yamalsky	4.54	3	Megino-Kangalassky	2.31	3
Yak-West	Suntarsky	4.39	2	Krasnoturansky	2.2	3
Yak-Center	Khangalassky	3.94	2	Magadan Oblast	2.17	3
Yak-Center	Yakutsk u.o.	3.83	2	Nadymsky	2.05	3
Yak-Center	Churapchinsky	3.29	2	Gorny	1.96	2
YANAO	Nadymsky	3.17	2	Sayansky	1.95	2
Komi	Sosnogorsky	2.64	2	Tattinsky	1.82	2
Yak-Arctic	Zhigansky	2.33	1	Priluzsky	1.81	2
Yak-Centre	Tattinsky	2.12	1	Suntarsky	1.79	2
YANAO	Priuralsky	2.07	1	Inta u.o.	1.67	2
Yak-East	Tomponsky	2.03	1	Pechora u.o.	1.6	2
Yak-East	Ust-Maisky	1.97	1	Srednekolymsky	1.27	2
Komi	Inta u.o.	1.88	1	Kosinsly	1.22	2
Komi	Ukhta u.o.	1.58	1	Dudinka u.o.	1.15	2
Krasnoyarsk	Abansky	1.48	1	Gainsky	1.08	2
Krasnoyarsk	Sayansky	1.48	1	Izhemsky	0.91	2
Komi	Priluzsky	1.41	1	Elizovsky	0.9	2
KPAO	Gainsky	1.37	1	Oimyakonsky	0.84	2
Yak-Arctic	Verkhoyansky	1.34	1	Kobiaisky	0.79	2
Komi	Syktyvkarsky u.o.	1.23	1	Olekminsky	0.77	2
Yak-Arctic	Nizhnekolymsky	1.17	1	Usinsk u.o.	0.66	2
Komi	Izhemsky	0.99	1	Chukotka AO	0.63	2
Komi	Pechora u.o.	0.95	1	Surgutsky	0.56	2
KPAO	Chusovskoy u.o.	0.94	1	Irbeisky	0.52	2
Yak-Arctic	Verkhnekolymsky	0.91	1	Yamalsky	0.52	2
Yak-Centre	Megino-Kangalassky	0.88	1	Koryak AO	0.51	2
KHMAO	Kondinsky	0.85	1	Kuraginsky	0.51	2
Komi	Syktyvdinsky	0.82	1	Idrinsky	0.49	2

Table 1. *Cont.*

	Hazard for Cattle				Hazard for People		
Subject of RF	**Municipal District**	HI_{terr}	**Score**		**Municipal District**	HI_{pop}	**Score**
Yak-Arctic	Bulunsky	0.81	1		Priuralsky	0.48	2
Yak-Arctic	Momsky	0.78	1		Kondinsky	0.48	2
KPAO	Kosinsky	0.68	1		Ust-Kulomsky	0.47	2
KPAO	Kudymkarsky	0.68	1		Ust-Yeniseysky	0.36	2
Kamchatka	Elizovsky	0.57	1		Kniazhpogostsky	0.31	2
Krasnoyarsk	Minusinsky	0.55	1		Kolsky	0.25	2
Krasnoyarsk	Krasnoturansky	0.55	1		Tomponsky	0.19	1
Komi	Ust-Kulomsky	0.53	1		Evenk AO	0.17	1
KHMAO	Berezovsky	0.5	1		Ust-Maisky	0.15	1
KHMAO	Surgutsky	0.47	1		Berezovsky	0.13	1
Komi	Usinsky u.o.	0.47	1		Verkhoyansky	0.11	1
Taymyr	Khatangsky	0.45	1		Leshukonsky	0.09	1
Yak-Arctic	Eveno-Batyntaisky	0.45	1		Mezensky	0.08	1
Komi	Knyazhpogostsky	0.41	1		Oleneksky	0.08	1
Krasnoyarsk	Irbeisky	0.37	1		Zhigansky	0.07	1
Krasnoyarsk	Lesosibirsk u.o.	0.32	1		Nizhnekolymsky	0.06	1
Arkhangelsk	Leshukonsky	0.31	1		Verkhnekolymsky	0.06	1
Arkhangelsk	Mezensky	0.31	1		Momsky	0.03	1
Krasnoyarsk	Idrinsky	0.27	1		Bulunsky	0.03	1
Krasnoyarsk	Kuraginsky	0.27	1		Eveno-Batyntaisky	0.02	1
Murmansk	Kolsky	0.17	1		Khatangsky	0.02	1

Source: Authors' calculations, statistical data. This table was originally published in [18]. NAO = Nenets Autonomous Oblast (Region); YANAO = Yamal-Nenets Autonomous Oblast; KHMAO = Khanty-Mansi Autonomous Oblast; KPAO = Komi-Permiatsky Autonomous Oblast; Yakutia is subdivided into the five economic zones: Arctic, Centre, West, East, and South; u.o. = urban okrug (district). The background color helps distinguish scores 6, 2, 4 from 5, 3, 1.

Paleolithic viruses can also be released in ambient air during permafrost degradation. This potential source of health risks has been insufficiently studied so far, but there are limited data on the circulation of paleoviruses between ecosystems [38]. Russian biologists have published several studies of the microbial communities in permafrost ecosystems [39]. High prevalence of the pathogen and 'suspected pathogen' bacteria in the Arctic ecosystems creates a demand for epidemiologic surveillance, including monitoring of ecosystem compartments and media (water, snow, air, soil, and frozen soil). The collected samples should be screened by molecular genetics methods, and the pathogenic properties of the collected microbial communities should be thoroughly studied. There are also other directions of research [40].

A permanent loss of permafrost areas drives the taiga north, where it replaces the tundra ecosystems, which, from an epidemiological standpoint, has its negative consequences. The habitats of rodents and insects shift northward, and many such species transmit infectious diseases. Global warming influences the prevalence of natural focal infections changing the environmental conditions and the life cycles of diseases' vectors and agents. Climate-dependent infections become the important sources of health risks. These infections include hemorrhagic fever with kidney syndrome, tick-borne encephalitis, and Lyme disease. Under the ongoing changes in climate and land use, assessment of risks for people and animals becomes a quite sophisticated and difficult task due to lack of knowledge about the prevalence, diversity, and distribution of the pathogens. The regional studies of quantitative relationships between climate change and disease prevalence are still quite limited.

The results of the long-term program of environmental and epidemiologic monitoring of tick-borne encephalitis (TBE) showed a statistically significant increase in the prevalence of this disease near the northern border of the tick habitat. A nearly 60-fold increase in TBE incidence was reported between the baseline period of 1980–1989 and the observation period of 2000–2009 in Archangelsk Oblast. Climate change could be the most important contributing factor for this increase. The northern boundary of the ixodid tick (*Ixodidae*) habitat shifted approximately 150–200 km north during the 40-year period of monitoring in Archangelsk Oblast. A similar, albeit less pronounced, increasing trend in TBE incidence was reported in the neighboring Komi Republic [41] and North Sweden [42]. Air temperature principally limits the northern boundary of the tick habitat in the taiga because this species can develop only if the mean daily temperature exceeds 5 °C [43]. An analysis of the blood serum of the donors who never had this disease or a vaccine against it showed a three- to fourfold increase in the prevalence of IgG (immunoglobulin G) antibodies to tick-borne encephalitis during the 12-year period between 2001 and 2013. The prevalence increased from 3.5% to 13.7%. The increase was most pronounced for those donors who lived in the south districts, which confirmed the hypothesis about the northward migration of the infected tick and adaptation of both the virus and the tick to a harsh northern climate [41].

Global warming may bring about deterioration of drinking water quality in the Arctic because melting of ice leads to water erosion of contaminated lands, including household and industrial waste dumps, fuel depots that store gasoline, kerosene, diesel fuel. Poor quality of drinking water may cause the spread of intestinal infections. Such infections may also be triggered by the changes in the temperature regime of frozen food storages. The food products are stored in underground ice storages in the Russian Arctic, Northern Canada, and Alaska. The largest storage of frozen food in Chukotka (its area is 330 square meters) was constructed in the 1960s. Since then, the air temperature, monitored at the nearest weather station, has increased by 3.8–4.4 °C (0.67–0.77 °C per 10 years). A smaller-size storage has already broken down because of permafrost degradation [44]. A microbiologic analysis of air samples taken from such low-temperature storages identified the *Yersiniaceae bacteria*, which survive and retain viability at temperatures between −15 °C and −20 °C. These samples contained not only *Yersinia* but also toxic fungi (*Aspergillus, Mucor*), which may contaminate the foods of indigenous peoples of the North [45].

3.2. Climate Change and Permafrost Degradation Pose Risks of Contamination of Ambient Air with Toxic Metals

Numerous metal works, mining companies, coal-fired power plants, and other industrial facilities release large quantities of toxic metals in ambient air in many regions of the Russian Arctic. The residents of industrialized areas are exposed to the combined effects of toxic metals in the air and extreme heat during the heat waves, which become more frequent. There are plans to increase the production of polymetallic ores, especially zinc and lead, in Spitsbergen Island and Novaya Zemlya. A new ore-mining plant is being constructed in Chukotka for the production of tin, copper, wolfram, and other metals. It is likely that new plants will be constructed in Yakutia for the mining of lead, mercury, copper, and other metals.

Norilsk Nickel is the largest mining and processing plant in the Arctic. It produces more than 200,000 tons of nickel annually, while 180,000 residents of Norilsk are exposed to noxious air pollution from this plant. Another 80,000 residents of the Kola Peninsula are exposed to the emissions of its daughter company, which operates the mining plants in the towns of Monchegorsk, Nickel, and Zapolyarny. Coagulation of toxic metals in ultrafine airborne suspended particles with sizes ≤5 µm (micrometers) creates an important source of carcinogenic risk for the local residents. The levels of nickel in ambient air in Norilsk used to be very high until recently (5–10 years ago), when the levels exceeded the maximum allowable concentration (MAC) by 15–20 times; today the pollution levels decreased as a result of the phase-out of several production facilities [46]. Long-term emissions of toxic metals in ambient air contaminated the soil as well. The levels of nickel in the soil exceeded the applicable MAC by a factor of 40 in some areas of the Kola Peninsula. In some places, the soil was heavily contaminated by lead (6 MAC) and cobalt (5 MAC) [47]. Coal mining, transportation, and combustion are associated with the emissions of certain air pollutants. The largest coal mines are situated near the towns of Vorkuta and Inta in the Komi Republic.

In these towns, the annual average levels of total suspended particulates (TSP) gradually decreased from 240 μg/m^3 in 2015 to 150 μg/m^3 in 2018 [48], still exceeding the allowable standards. Coal mining in other Arctic territories (Taymyr, Yakutia, Chukotka) also pollutes ambient air with suspended particulates, including the ultrafine fraction, and coagulated toxic metals, but the numeric data on the pollution levels are absent.

The problem of mercury pollution in Arctic ecosystems deserves special attention, as the estimated reserves of this metal in the Russian Arctic are 800,000 tons [49]. Health risks of mercury and its organic compounds have been thoroughly studied, which resulted in the adoption of the Minamata Convention on Mercury in 2009, aimed at the control and eventual prohibition (by 2020) of the manufacture, export, import, and utilization of this metal. The Russian Federation signed this convention in 2014 and ratified it in 2017. Mercury can be released in the Arctic environment during its direct mining in Yakutia and Chukotka or, alternatively, during gold mining in Magadan Oblast. Mercury is also emitted in ambient air by large metal works and refineries and copper and nickel smelters.

Mercury used to be released in the aquatic ecosystems in the Arctic by gold refineries [50]. Golf mining in the Yakutia and Magadan regions has a very long history. Recently, a new project on the massive development of the Yana-Kolyma gold-mining province was launched. There are about 300 gold mines in Magadan Oblast and many gold refineries [51]. Open-pit gold mining in the valleys of small rivers is accompanied by the release of mercury in the rivers and streams; mercury can be present in drinking water sources [52]. Gold mining is associated with pollution of the environment by other toxic metals: lead, copper, arsenic, and cadmium. The amalgam method of gold ore separation is especially harmful to the environment as it involves mercury as a chemical reagent, and this method was banned only recently (in 1989). Before the prohibition, large quantities of mercury were routinely released in the watercourses and accumulated in the bottom sediments for several decades. Methylmercury accumulated in fish through the food chains so that fishing and drawing drinking water from the surface sources still pose considerable health risks in the gold mining regions. Data on mercury concentrations in the environment are largely absent or rare, which precludes quantitative assessment of health risks of mercury pollution. Russian sanitary surveillance service grades the water in Aldan River as “extremely polluted”, and this river serves as a source of drinking water. MAC standards for copper and mercury were violated in 56–86% of water samples drawn from Aldan River, but the actual concentrations have not been reported [53]. The mercury content in freshwater fish caught in the gold-mining regions of Yakutia exceeded the applicable MAC standard threefold. Notably, the residents of Yakutia consume more fish in their diets than the residents of other Russian regions [54].

Mercury emanations from permafrost may become a new source of environmental pollution, as permafrost remains the largest global reservoir of this metal. Permafrost degradation will inevitably release large quantities of mercury in the aquatic ecosystems. An estimated global annual release of mercury as a result of the current degradation of permafrost is 20 tons/year, and this metal ultimately goes to the largest rivers of the Russian Arctic (Yenisei, Kolyma, Ob, Lena) and North America (Mackenzie and Yukon), which flow into the Arctic Ocean; the releases of mercury increase every decade [55]. At the same time, a net decrease in total mercury content (including methylmercury) in the *Lota* fish tissue has been reported. The measurements of total mercury were averaged for the low reaches of the three rivers of European Russia (Northern Dvina, Mezen, Pechora) and the five Siberian rivers (Yenisei, Kolyma, Pyasina, Ob, Lena). During the period between 1980 and 2001, the mercury content decreased by 2.6% per year on average. The total reduction was 39% (from 0.171 to 0.104 mkg/g of wet weight). Interestingly, the total lead content in *Lota* fish tissue in the North American Arctic increased during the same period [56,57]. Possible reasons for the opposite trends in the Russian and American Arctic could be tied to the general circulation patterns in the atmosphere, sedimentation of airborne aerosols, consequences of climate change, anthropogenic factors, nature conservation activity, and specific measures aimed at the control of mercury-containing waste in the environment in the Western and the Eastern Hemispheres.

In the framework of the AMAP program, a health risk assessment project was launched, and mercury content in the blood of men and women who lived in various regions of the Russian Arctic, from Murmansk to Chukotka, was measured. The findings of this project indicated that the blood mercury content was lower than the blood mercury reference value recommended by WHO [58]. However, there are no data on the intake of mercury or methylmercury by the indigenous peoples of the North who consume the polluted fish and seafood.

3.3. Climate Change, Permafrost Degradation, Stability of Buildings, and Engineered Infrastructure

The accessibility of health care services remains an important contributor to overall life quality and public health of the Arctic residents. Another aspect of life quality is related to comfort living conditions, including stability of residential houses and hospitals, and year-round road conditions vital for transportation. Permafrost degradation affects the stability of buildings' foundations and various objects of engineered infrastructure. The risks for infrastructure are the greatest in Nenets AO, Yamal-Nenets AO, the northern part of the Krasnoyarsk region, Sakha Republic (Yakutia), Magadan Oblast, and Chukotka AO. Under the IPCC RCP8.5 global warming scenario, the authors estimated the total annual economic costs that would be needed to overcome the consequences of permafrost degradation. The calculations were made for the following three sectors of the economy: maintenance of the motorway network, residential buildings, and public hospitals. The total annual outlays can reach USD 1.1 billion under the scenario of slow permafrost thawing and USD 4.8 billion under the scenario of fast thawing. Table 2 summarizes the results of calculations by economic sectors and regions.

Table 2. Economic losses due to the maintenance of the social infrastructure built on permafrost under low, medium, and high permafrost degradation rates.

Region	Regional GDP in 2019, Million USD	Expected Annual Economic Loss Due to Permafrost Degradation, Million USD								
		Health Care			Residential Housing			Motorway Network		
		Low	Medium	High	Low	Medium	High	Low	Medium	High
Komi Republic	29,415	8.72	8.72	8.72	120.82	120.82	120.82	27.28	27.28	27.28
Nenets AO	13,515	0.02	6.34	6.35	0.41	126.12	126.12	9.35	10.33	11.31
Khanty-Mansi AO	186,247	0.00	0.26	3.91	0.00	3.27	45.71	2.79	2.79	2.79
Yamal-Nenets AO	126,554	29.4	37.09	37.09	448.9	566.53	566.5	28.73	35.25	41.63
Krasnoyarsk region	109,887	0.03	24.92	33.29	0.41	255.92	342.0	57.35	57.81	58.27
Sakha Republic (Yakutia)	49,809	0.00	12.34	185.51	0.00	155.92	2 345	303.0	343.99	384.9
Magadan Oblast	8718	0.00	0.97	36.35	0.00	5.31	193.8	45.37	48.37	51.55
Chukotka AO	3873	0.14	0.14	19.17	1.22	1.22	138.3	46.82	48.30	49.78
Total	528,017	38.3	90.80	330.4	571.8	1 235.1	3 878	520.7	574.11	627.5

Source: Authors' calculations.

Economic analysis by sectors showed that the expected economic damage in the health-care sector was actually quite small, less than 0.001% of the regional GDP. However, the indirect losses could arise from relocation of health-care centers, temporary unavailability of health-care services and hospitals, additional demands for health-care services where the hospitals are still available, increase in waiting times, and so forth. Transport accessibility of medical services can become a crucial issue in the conditions of low population density and a scattered network of health-care facilities. For example, the settlements in the north of the Krasnoyarsk region near the Arctic Ocean can only be accessed by air. A temporary closing of a hospital would require additional air transportation expenses and would lead to an increase in waiting times.

The greatest portion of the expected economic loss falls to the residential sector. The estimated annual costs vary between USD 0.5 and 3.8 billion. Again, the possible consequences can be far-reaching. The share of urban population in the Russian Arctic is about 80%, which is 5% greater than the Russian average value, and the total population of the studied regions is 7.5 million. The total area of residential housing there was 170 million m^2 in 2018. Most urban residents there live in multistory houses and use centralized communal services. Some of these houses (4.3 million m^2) are already in disrepair or emergency state. The construction costs in the Arctic are much higher than those in Central Russia (about 68,000 RUR/m^2).

The current rate of commissioning of new residential housing in the Arctic (about 500,000 m^2 per year) should be nearly doubled if one wants to compensate for the decaying houses as a result of permafrost degradation.

The economic loss in the road transportation sector due to permafrost degradation can be USD 0.5–0.6 billion annually. The greatest damage is expected in Yakutia because of its well-developed motorway network. The economic estimates presented here are based on the existing road networks and do not account for any future changes. The existing motorways in the permafrost regions are already old enough; the authors estimated the total length of these roads to be 35,471 km, of which only 3% are paved and 97% are dirt roads.

3.4. Climate Change and Adverse Weather Conditions

Extreme weather events create significant risks to environmental health in Russia due to its very large territory and complex geographical and environmental conditions. In Russian Arctic, such events include snowstorms, ice tsunami, coastal erosion, white mist, and abrupt changes in weather in time and space induced by varying local conditions. Extreme weather events cannot be avoided, but their adverse consequences to public health can be mitigated by the implementation of early warning systems, preparedness, and rapid response of health-care system to such events. The health-care sector and public administration in general should ensure their stable and sustainable operations in the conditions of global warming. One of the possible improvements in the public management could come from the optimization of transportation between the settlements and the hospitals. The authors applied the modern mapping methods in Archangelsk Oblast and Nenets AO and showed that 25% of local residents experienced considerable delays in emergency transportation to the nearest hospital or ambulatory. Health risk distribution maps were developed for these territories. Implementation of road network graphs in the public health sector helped to optimize the locations of health-care centers, including specialized hospitals, and emergency transportation logistics. Even a short-term closing of the existing hospitals poses significant health risks for the residents of the remote settlements in the Krasnoyarsk region, Sakha Republic (Yakutia), Nenets AO, Yamal-Nenets AO, Magadan Oblast, and Chukotka AO. Most medical services there are offered by the obstetric and paramedics stations and small polyclinics usually stationed in the administrative centers of municipal districts. The distances between the nearest stations can reach several hundred kilometers [22].

Table 3 summarizes the populations of administrative regions within the Russian Arctic permafrost belt and the estimated numbers of Siberian anthrax cattle burial sites.

Table 3. Population of the Russian Arctic in 2021, including those who live in the conditions of permafrost degradation.

Region	Population, Number of People					Number of Siberian Anthrax Cattle Burials in Frozen Soils
	Total		Arctic Zone of Russia		Areas of Permafrost Degradation	
	Urban	Rural	Urban	Rural		
Komi Republic	637,072	176,518	135,063	17,509	240,539	28
Archangelsk Oblast	888,896	238,155	591,280	45,052	0	84
Nenets AO	32,948	11,441	32,948	11,441	44,389	20
Murmansk AO	675,190	57,674	675,190	57,674	0	2
Khanty-Mansi AO	1,563,020	124,634	0	0	341,868	21
Yamal-Nenets AO	459,078	87,932	459,078	87,932	547,010	8
Krasnoyarsk region	2,217,054	638,845	208,994	21,135	544,954	39
Sakha Republic (Yakutia)	651,070	330,901	26,107	41,691	981,971	270
Kamchatka region	245,188	66,479	0	0	311,667	n/a
Magadan Oblast	133,607	5427	0	0	139,034	n/a
Chukotka AO	35,242	14,285	35,242	14,285	49,527	n/a
Total	7,538,365	1,752,291	2,163,902	296,719	3,200,959	472

Source: Authors' calculations, statistical data, reference [31].

4. Conclusions

Permafrost is an important environmental feature of the Russian Arctic, which significantly affected and still affects the lifestyles, public health, and economy of both the indigenous and migrant populations in this region. The specific permafrost conditions determined the methods for the construction of residential housing and engineered infrastructure. Frozen soils contain harmful bacteria, viruses, and toxic chemicals, including mercury. In several past decades, global climatic changes and, most importantly, rapid increase in ground-level air temperatures dramatically affected the stability of permafrost and caused its thawing and degradation. Permafrost degradation turned the whole region in the zone of high investment risk, undermined social well-being, and contributed to health risks experienced by a significant portion of the Arctic population.

The existing problem of permafrost degradation needs to be addressed, but the minimization of the adverse consequences of permafrost degradation requires considerable financial outlays and administrative efforts. The prediction of the extent and rate of future changes is accompanied by high uncertainties and unresolved scientific problems; it is also quite difficult to estimate the ability of the state and the people to adapt to such changes. The assessment of costs of restoration of the infrastructure objects in different economic sectors, which may be destroyed due to permafrost degradation, has been conducted under several climate change scenarios. Total costs may vary between 0.21% and 0.91% of the annual gross regional product in the selected regions. The economic consequences of permafrost degradation can actually be even more far-reaching. The costs in the health-care sector due to permafrost degradation may reach 3% of the total annual health-care budget. Depending upon the rates of permafrost degradation, the demand for new housing construction will be between 280,000 m^2 and 1,500,000 m^2 [23,24]. New housing will be needed to compensate for the losses in the residential sector due to permafrost degradation. For comparison, the total area of residential housing in the Russian North is currently 2800 m^2, so this will be quite a challenge for the regional economies. About 3.2 million people live in the permafrost regions of the Russian Arctic, and 81% of these people live in the cities. Urban populations are usually more susceptible to contagion of infectious diseases. COVID-19 provided an example of such vulnerability, because the highest infection rates were detected among workers in oil and gas mining companies who work in small isolated teams and live together in dormitories. The risks associated with permafrost degradation include the release of mercury, and other toxic substances, to the environment during permafrost thawing, as well as destruction of buildings' foundations, water supply and wastewater disposal mains, and deterioration of housing and living conditions. There are concerns over possible closing of medical facilities, inaccessibility of health-care services, increase in patients' waiting times, and emerging infectious diseases. While certain direct economic losses and risks can be identified, predicted, and assessed, it is hardly possible to foresee numerous indirect consequences and the associated economic costs. There are reasons to believe that indirect damage to the economy as a result of permafrost degradation can be much greater than direct losses.

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References

1. Edel'geriev, R.S.K.; Romanovskaya, A.A. New approaches to the adaptation to climate change: The Arctic zone of Russia. *Russ. Meteorol. Hydrol.* **2020**, *45*, 305–316. [CrossRef]
2. Iglovskii, S.A. Anthropogenic transformation of permafrost conditions of the European north of Russia and their consequences. *Arct. North* **2013**, *10*, 107–1124. (In Russian)
3. Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M.I.; et al. (Eds.) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021; Available online: https://www.ipcc.ch/report/ar6/wg1/#FullReport (accessed on 20 December 2021).
4. Arctic and Antarctic Research Institute. Available online: http://www.aari.nw.ru (accessed on 20 December 2021).
5. Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet). Report on Climate Features on the Territory of the Russian Federation in 2020. Moscow. 2021; 104p. Available online: https://www.meteorf.ru/upload/pdf_download/doklad_klimat2020.pdf (accessed on 21 March 2022). (In Russian)
6. Desyatkin, R. Climate change and the dynamics of the center's permafrost ecosystems of continental cryolithozone of the northern hemisphere. *Vestnik RAS* **2018**, *88*, 1113–1121. [CrossRef]
7. Shirokov, R.S. Formation of geoecological conditions of the coastal marine region of the Western Yamal under climate change. *Belgorod State Univ. Sci. Bull. Nat. Sci. Ser.* **2019**, *43*, 412–424. [CrossRef]
8. Revich, B.A.; Shaposnikov, D.A.; Shkolnik, I.M. Projections of temperature-dependent mortality in Russian subarctic under climate change scenarios: A longitudinal study across several climate zones. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *606*, 012050. [CrossRef]
9. Nelson, F.E.; Anisimov, O.F.; Shiklomanov, N.L. Subsidence risk from thawing permafrost. *Nature* **2001**, *410*, 889–890. [CrossRef]
10. Goncharova, O.Y.; Matyshak, G.V.; Bobrik, A.A.; Moskalenko, N.G.; Ponomareva, O.E. Temperature regimes of Northern Taiga soils in the isolated permafrost zone of Western Siberia. *Eurasian Soil Sci.* **2015**, *48*, 1329–1340. [CrossRef]
11. Pavlov, A.V.; Malkova, G.V. Small-scale mapping of trends of the contemporary ground temperature changes in the Russian North. *Earths Cryosphere* **2009**, *4*, 32–39. (In Russian)
12. Mokhov, I.I.; Eliseev, A.V. Modeling of global climate variations in the 20th–23rd centuries with new RCP scenarios of anthropogenic forcing. *Dokl. Earth Sci.* **2012**, *443*, 732–736. [CrossRef]
13. Revich, B.A.; Shaposhnikov, D.A.; Anisimov, O.A.; Belolutskaya, M.A. Heat and cold waves in cities located in the Arctic and Subarctic zones as risk factors for increasing population mortality on the example of Arkhangelsk, Murmansk and Yakutsk. *Hyg. Sanit. Russ. J.* **2018**, *97*, 791–799. (In Russian) [CrossRef]

14. Revich, B.A.; Shaposhnikov, D.A.; Anisimov, O.A.; Belolutskaya, M.A. Impact of Temperature Waves on the Health of Residents in Cities of the Northwestern Region of Russia. *Stud. Russ. Econ. Dev.* **2019**, *30*, 327–333. [CrossRef]
15. Grigorieva, E.A.; Revich, B.A. Health Risks to the Russian Population from Temperature Extremes at the Beginning of the XXI Century. *Atmosphere* **2021**, *12*, 1331. [CrossRef]
16. Revich, B.A. Climate Change and Health of the Population of the Russian Arctic. *Environ. Plan. Manag.* **2008**, *71*, 109–121. (In Russian)
17. Svinoboev, A.N.; Neustroeva, A.B. Change of climate and living conditions in the North in perception of the indigenous population. *Urban Stud.* **2017**, *4*, 28–39. [CrossRef]
18. Revich, B.A.; Shaposhnikov, D.A.; Raichich, S.R.; Saburova, S.A.; Simonova, T.G. Creating zones in administrative districts locate in the Russian Arctic region specific as per threats of cattle burials decay due to permafrost degradation. *Health Risk Anal.* **2021**, *1*, 115–125. [CrossRef]
19. Vasiliev, A.A.; Gravis, A.G.; Gubarkov, A.A.; Drozdov, D.S.; Korostelev, Y.V.; Malkova, G.V.; Oblogov, G.E.; Ponomareva, O.E.; Sadurtdinov, M.R.; Streletskaya, I.D.; et al. Permafrost degradation: Results of the long-term geocryological monitoring in the western sector of Russian Arctic. *Earths Cryosphere* **2020**, *24*, 15–30. [CrossRef]
20. Federal Service for Veterinary and Phytosanitary Surveillance Sanitary and Veterinary Rules of Russian Agricultural Surveillance. Collection, Utilization and Removal of Biological Waste. 1995. Available online: https://fsvps.gov.ru/fsvps/laws/165.html (accessed on 12 September 2020).
21. Osipov, V.I.; Sergeev, D.O. Influence of permafrost melting on the functioning of infrastructure in the Far North. In Proceedings of the the Meeting of Scientific Advisory Panel of Russian State Committee on Natural Resources, Moscow, Russia, 25 June 2020.
22. Shartova, N.V.; Grischenko, M.Y.; Revich, B.A. Geographical accessibility of health services based on open data in the Arkhangelsk region. *Soc. Asp. Popul. Health* **2019**, *65*, 1–29. Available online: http://vestnik.mednet.ru/content/view/1114/30/lang,ru (accessed on 21 March 2022). (In Russian). [CrossRef]
23. Porfiriev, B.N.; Eliseev, D.O.; Streletskiy, D.A. Economic assessment of permafrost degradation effects on healthcare facilities in the Russian Arctic. *Her. Russ. Acad. Sci.* **2021**, *91*, 677–686. [CrossRef]
24. Porfiriev, B.N.; Eliseev, D.O.; Streletskiy, D.A. Economic Assessment of Permafrost Degradation Effects on the Housing Sector in the Russian Arctic. *Her. Russ. Acad. Sci.* **2021**, *91*, 17–25. [CrossRef]
25. Porfiriev, B.N.; Eliseev, D.O.; Streletskiy, D.A. Economic assessment of permafrost degradation effects on road infrastructure sustainability under climate change in the Russian arctic. *Her. Russ. Acad. Sci.* **2019**, *89*, 567–576. [CrossRef]
26. Streletskiy, D.A.; Suter, L.J.; Shiklomanov, N.I.; Porfiriev, B.N.; Eliseev, D.O. Assessment of climate change impacts on buildings, structures and infrastructure in the Russian regions on permafrost. *Environ. Res. Lett.* **2019**, *14*, 025003. [CrossRef]
27. Shatilovich, A.V.; Shmakova, L.A.; Gubin, S.V.; Gilichinskii, D.A. Viable Protozoa in the Arctic Permafrost. *Earths Cryosphere* **2010**, *14*, 69–78. (In Russian)
28. Yegorov, I.Y.; Maramovich, A.S.; Botvinkin, A.D. *Epidemiological Surveillance over Highly Dangerous and Natural Focal Infections in the Extreme North*; Kuduk: Yakutsk, Russia, 2000; 248p. (In Russian)
29. Repin, V.; Pugachev, V.; Taranov, O.; Totmenina, O.; Emelianova, E.; Torok, T.; Belikov, S. What secrets does Yukagir mammoth brain harbor? In Proceedings of the International Symposium on Yukagir Mammoth: Recent Advance in Yukagir Mammoth Researches, Japan Association for the 2005 World Exposition, Aichi, Japan, 18 June 2005; p. 18.
30. Tarabukina, N.P.; Neustroev, M.P.; Skryabina, M.P.; Stepanova, A.M.; Parnikova, S.I.; Bylgaeva, A.A.; Neustroev, M.M. The role of Bacillus bacteria in conservation of the remains of mammoth in permafrost. *Probl. Reg. Ecol.* **2018**, *6*, 22–27. (In Russian) [CrossRef]
31. Russian Service for Supervision of Consumer Protection and Human Welfare (Rospotrebnadzor). *Cadaster of Stationary Unfavorable by Anthrax Points in the Russian Federation*; Intersen Publishers: Moscow, Russia, 2005; 829p. (In Russian)
32. Revich, B.; Podolnaya, M. Thawing of permafrost may disturb historic cattle burial grounds in East Siberia. *Glob. Health Action* **2011**, *4*, 8482. [CrossRef]
33. Popova, A.Y.; Kulichenko, A.N. (Eds.) *The Experience of Elimination of Anthrax Outbreak in the Yamal in 2016*; Print-2: Izhevsk, Russia, 2017; 313p. (In Russian)
34. Simonova, E.G.; Kartavaya, S.A.; Titkov, A.V.; Loktionova, M.N.; Raichich, S.R.; Tolpin, V.A.; Lupyan, E.A.; Platonov, A.E. Anthrax in the Territory of Yamal: Assessment of Epizootiological and Epidemiological Risks. *Probl. Part. Danger. Infect.* **2017**, *1*, 89–93. [CrossRef]
35. Perevertin, K.A.; Vasil'ev, T.A. Elevated risks of paleobiological contamination caused by global warming. In Proceedings of the Sixth Conference "Mathematical Modeling in Ecology" EkoMatMod-2019, Puschino, Moscow Region, Russia, 26–29 September 2019; pp. 158–160. (In Russian).
36. Dyagilev, G.T.; Neustroev, M.P. Epidemiological and epizootological situation on anthrax in the republic of Sakha (Yakutia). *Vet. Med. Feed.* **2019**, *7*, 11–13. [CrossRef]
37. Dugarzhapova, Z.F.; Chesnokova, M.V.; Ivanova, T.A.; Kosilko, S.A.; Balakhonov, S.V. Improvement of Methodical Approaches to Investigation of Anthrax Burials and Animal Burial Sites. *Probl. Part. Danger. Infect.* **2019**, *4*, 41–47. [CrossRef]
38. Elpiner, L.I.; Dzyuba, A.V. Medical and environmental aspects of the degradation of the permafrost zone: Problem of paleoviral contamination. *Hyg. Sanit. Russ. J.* **2017**, *96*, 706–711. [CrossRef]

39. El-Registan, G.I.; Nikolaev, Y.A.; Mulyukin, A.L.; Loikaw, N.G.; Demkina, E.V.; Gaponov, A.M.; Tutelian, A.V.; Pisarev, V.M. The phenomenon of persistence—The forms and mechanisms of survival of populations. *Med. Alph.* **2014**, *2*, 49–54. (In Russian)
40. Kraeva, L.A.; Panin, A.L.; Goncharov, A.E.; Belov, A.B.; Vlasov, D.Y.; Kirtsideli, I.Y.; Goncharov, N.E.; Baranov, I.V.; Sboychakov, V.B. Epidemiological significance of microbiota monitoring of arctic settlements along the Northern Sea Route. *Marine Medicine Russ. J.* **2021**, *7*, 23–33. [CrossRef]
41. Tronin, A.A.; Tokarevich, N.K. Average annual temperature of atmospheric air and the number of tick victims in the European North of Russia. In Proceedings of the III International Scientific and Practical Conference "Health Problems and Ensuring Sanitary and Epidemiological Well-Being of the Population in the Arctic", Saint-Petersburg, Russia, 21–22 October 2021; pp. 230–236. (In Russian).
42. Lindgren, E.; Gustafson, R. Tick-borne encephalitis in Sweden and climate change. *Lancet* **2001**, *358*, 16–18. [CrossRef]
43. Balashov, Y.S. *Ticks—Parasites and Disease Vectors*; Nauka: St. Petersburg, Russia, 1998; 287p. (In Russian)
44. Neustroev, M.P.; Tarabukina, N.P.; Maksimova, A.N.; Stepanova, A.M. Microbiota and sanitation of underground glaciers during food storage. *Yakut Med. J.* **2019**, *1*, 79–82. [CrossRef]
45. Komova, N.N.; Maslakov, A.A. Monitoring of the thermal condition of underground storage facilities in Eastern Chukotka. In Proceedings of the Second Russian Scientific Conference "Monitoring of the State and Pollution of the Environment. Ecosystems and Climate of the Arctic Zone", Moscow, Russia, 22–27 November 2020; pp. 236–239. (In Russian).
46. Kasikov, A.G. Particulate Emissions from Copper-Nickel Production and the Consequences of their Impact on Human Body in the Far North. *Her. Kola Sci. Cent. RAS* **2017**, *4*, 58–63. (In Russian)
47. Russian Service for Supervision of Consumer Protection and Human Welfare (Rospotrebnadzor). State Report "On the State of Sanitary and Epidemiological Welfare of the Population in the Murmansk Region in 2018". Available online: http://51.rospotrebnadzor.ru/content/866/44340/ (accessed on 21 March 2022). (In Russian)
48. Ministry of Natural Resources and Environmental Protection of the Komi Republic. *State Report "On the State of the Environment of the Komi Republic in 2018"*; Territorial Information Fund of the Komi Republic: Syktyvkar, Russia, 2019; 163p.
49. Lim, A.G.; Sonke, J.E.; Krickov, I.V.; Manasypov, R.M.; Loiko, S.V.; Pokrovsky, O.S. Enhanced particulate Hg export at the permafrost boundary, western Siberia. *Environ. Pollut.* **2019**, *254*, 113083. [CrossRef] [PubMed]
50. Ministry of Natural Resources and Environmental Protection of Magadan Region. Report on the Environmental Situation in the Magadan Region in 2017. Available online: https://minprirod.49gov.ru/common/upload/23/editor/file/Ob_ekologicheskoy_situatsii_za_2017_na_publ.pdf (accessed on 2 June 2021). (In Russian)
51. Roslyakov, N.A.; Kirillova, O.V. Mercury pollution of environmental by gold mining in Russia. *Chem. Sustain. Dev.* **1995**, *3*, 43–55. (In Russian)
52. Sotnikov, V.I. Environmental impact of mineral deposits and their development. *Sorovsky Educ. J.* **1997**, *5*, 62–65. (In Russian)
53. Ministry of Natural Resources and Environmental Protection of Sakha Republic. Summary of State Report on the Environmental Situation in the Republic of Sakha (Yakutia) for 2018. Available online: https://minpriroda.sakha.gov.ru/uploads/ckfinder/userfiles/2021/04/13/files/%D0%93%D0%94%202018.pdf (accessed on 18 August 2021).
54. Tyaptirgyanov, M.M.; Tyaptirgyanova, V.M. Ecologic and hygienic assessment of accumulation of mercury in bodies and tissues of river fish of Yakutia. *Yakut Med. J.* **2015**, *1*, 34–38. (In Russian)
55. Mu, C.; Zhang, F.; Chen, X.; Ge, S.; Mu, M.; Jia, L.; Wu, Q.; Zhang, T. Carbon and mercury export from the Arctic rivers and response to permafrost degradation. *Water Res.* **2019**, *161*, 54–60. [CrossRef] [PubMed]
56. Pelletier, A.R.; Castello, L.; Zhulidov, A.V.; Gurtovaya, T.Y.; Robarts, R.D.; Holmes, R.M.; Zhulidov, D.A.; Spencer, R.G.M. Temporal and Longitudinal Mercury Trends in Burbot (*Lota lota*) in the Eastern Arctic. *Environ. Sci. Technol.* **2017**, *51*, 13436–13442. [CrossRef] [PubMed]
57. Castello, L.; Zhulidov, A.V.; Gurtovaya, T.Y.; Robarts, R.D.; Holmes, R.M.; Zhulidov, D.A.; Lysenko, V.S.; Spencer, R.G.M. Low and Declining Mercury in Arctic Russian Rivers. *Environ. Sci. Technol.* **2014**, *48*, 747–752. [CrossRef] [PubMed]
58. Dudarev, A.A.; Dushkina, E.V.; Sladkova, Y.N.; Chupakhin, V.S.; Lukicheva, L.A. Levels of Exposure to metals in population of Pechenga district of Murmansk region. *Industr. Med.* **2016**, *6*, 11–16.