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Review

BIOLOGICAL RISK FACTORS IN THE RUSSIAN ARCTIC: A SCOPING LITERATURE REVIEW

V.P. Chashchin[1,2], N.V. Zaitseva[3,4], M.V. Chashchin[2], N.A. Sobolev[1,5], T.Yu. Sorokina[1], M.M. Shakirov[2]

[1]Northern (Arctic) Federal University named after M.V. Lomonosov, 17 Naberezhnaya Severnoi Dviny, Arkhangelsk, 163002, Russian Federation
[2]North-Western State Medical University named after I.I. Mechnikov, 41 Kirochnaya St., Saint-Petersburg, 191015, Russian Federation
[3]Federal Scientific Center for Medical and Preventive Health Risk Management Technologies, 82 Monastyrskaya St., Perm, 614045, Russian Federation
[4]Russian Academy of Sciences, 14 Leninskii Av., Moscow, 119991, Russian Federation
[5]M.V. Lomonosov Moscow State University, 1 Leninskie Gory, Moscow, 1119991, Russian Federation

The goal of the review is to study and summarize approaches to assessing, monitoring, predicting, and countering human health risks associated with the spread of virulent pathogens, parasites, and other biological hazards in the Russian Arctic regions.

A literature search was conducted from May to August 2024 using PubMed, Web of Science, Science Direct, and eLibrary.ru to identify studies on vector-borne pathogens, parasites, and other biological hazards in the Arctic. The review also considered phenomena of bioaccumulation of chemical contaminants in biological food chains that can cause increased susceptibility of humans to infections and the impact of climate change on biological risks in the Arctic. Of the 348 identified publications, 55 articles were selected that met the inclusion criteria.

The analysis revealed significant gaps in the literature on biological risk assessment related to primary data on Arctic zoonotic diseases, with the most limited information related to the sources and pathways of their spread by wild game species. Based on hazard identification, it was established that risk factors for the spread of zoonotic diseases include unfavorable living conditions (inferior quality of life), higher population density, low-quality environment, and socio-economic considerations. Migratory birds, fish, and animals can significantly contribute to the global spread and pandemics of infectious diseases. Improving our knowledge of wild bird and fish migration routes and vector-borne infectious diseases can help predict future outbreaks and epidemics. The analysis proposed a predictive model for assessing biological risk events associated with this migration.

Keywords: *Arctic, biological hazards, infectious diseases, health risk factors, pathogen transmission, migratory animals and insects.*

Any organism or biological material that can have an impact on wildlife and human health is referred to as a biological hazard in a broader sense. Predators, tamed and farm animals, parasites, viruses, bacteria, fungi, poisonous marine animals, plants, and their bio-

Valerii P. Chashchin – Honored Scientist of the Russian Federation, Doctor of Medical Sciences, Professor at the Department of Preventive Medicine and Health Protection (e-mail: valerych05@mail.ru; tel.: +7 (921) 958-88-85; ORCID: https://orcid.org/0000-0002-2600-0522).

Nina V. Zaitseva – Academician of the Russian Academy of Sciences, Doctor of Medical Sciences, Professor, Scientific Director (e-mail: znv@fcrisk.ru; tel.: +7 (342) 237-25-34; ORCID: http://orcid.org/0000-0003-2356-1145).

Maksim V. Chashchin – Doctor of Medical Sciences, Head of the Research Laboratory for Arctic Health (e-mail: max_chashchin@inbox.ru; tel.: +7 (921) 912-15-45; ORCID: https://orcid.org/0000-0001-6759-5481).

Nikita A. Sobolev – Candidate of Chemical Sciences, Researcher at the Department of Chemistry, Department of Medical Chemistry and Fine Organic Synthesis, Laboratory of Natural Humic Systems (e-mail: nikita.sobolev@kjemi.uio.no; tel.: +7 (960) 010-45-61; ORCID: https://orcid.org/0000-0002-8210-8263).

Tatiana Yu. Sorokina – Candidate of Law Sciences, Head of the Arctic Biomonitoring Laboratory, Department of International Law and Comparative Law (e-mail: t.sorokina@narfu.ru; tel.: +7 (902) 708-08-08; ORCID: https://orcid.org/0000-0002-4873-8747).

Munirdzhon M. Shakirov – Candidate of Medical Sciences, Senior Researcher at the Research Laboratory for Arctic Health (e-mail: m.shkirov@imed.pro; tel.: +7 (913) 880-11-71; ORCID: https://orcid.org/0000-0002-9828-4958).

toxins, which can result in infections, wounds, allergies, or poisoning, are among them. Humans may be at risk from any direct or indirect interaction with the self-replicating organisms such as plants, fungi, animals, protozoa, and monerans that are involved in the process of natural selection.

Features, source, and mode of exposure to a biological hazard all influence risks to the environment and human health (e.g., exposure to diseases or biotoxins because of contact with contaminated surfaces, eating contaminated food or water, getting bit by bloodsucking vectors, or interacting with animals).

Zoonotic diseases that are endemic, emerging, or re-emerging not only endanger humans and animals' health but also jeopardize the security of global health care. Zoonotic origins are estimated to account for up to 75 % of newly identified or emerging infectious diseases and 60 % of known infectious diseases. Infectious diseases cause 15.8 % of deaths worldwide and 43.7 % of deaths in low-resource countries [1, 2]. An estimated 2.7 million human deaths and 2.5 billion cases of illness are attributed to zoonotic diseases every year [3–5].

The aim of this review is to survey and summarize approaches to evaluating, monitoring, predicting and countering risks to human health associated with the spread of virulent pathogens, parasites, and other biological hazards across Russian Arctic regions.

To achieve this, **the following tasks** have been set:

– to examine published data to identify priority biohazards, related societal concerns, and measures of controlling global and interregional migration as well as endemic pathogens, parasites, and other biohazards in the Russian Arctic;

– to identify migratory species of wildlife capable of transferring pathogens into the Arctic, focusing especially on species being traditional foods of indigenous people;

– to assess biological risks related to remobilization of viable Paleo-pathogens from thawing permafrost soils caused by climate change;

– to recommend actions for controlling and preventing emerging and re-emerging infectious diseases that are spread through biological pathways for local public and health authorities at the community level.

Materials and methods. The full-text search for publications in English was carried out using article titles, authors, and keywords: "Arctic regions, biological hazards, biomonitoring, infectious diseases, food contaminants, human health risk factors, pathogen transmission, migratory animals and insects, climate change impact". The search of published scholarly articles, reports, and documents was completed over the period from May to August 2024, using main academic databases and webpages: PubMed®, the Centre for Research on the Epidemiology of Disaster (Emergency Disaster Database); and WHO, and CDC websites. Publications since 1998 were considered. Search for publications in Russian data sources was also based on the same keywords using e-Library platforms: elibrary (http://www.elibrary.ru), Scholar.ru (http://www.scholar.ru) and Cyber Leninka (https://cyberleninka.ru).

Out of all 348 identified publications, 54 papers were chosen for inclusion. Publications containing information on biological risks in the Arctic areas were selected for analysis. Most papers that included studies (n = 48) and case studies (n = 6) were based on secondary data, and most publications addressed northern regions, including the Arctic (n = 20). A thematic qualitative analysis of biological health risk factors was created by synthesizing the available evidence.

Results. ***Biological risk sources, transmission patterns, and health risk factors in the Arctic.*** Most infectious diseases are endemic or naturally focal in the Arctic, with limited spatiotemporal dynamics. The exceptions are some viral and bacterial infections, especially respiratory ones, the spread of which might be epidemic or pandemic.

Biological pathways, like migration of people, wild birds, fish, insects, and marine mammals, play a predominant role in transmitting virulent pathogens to humans since they serve as primary reservoirs and carriers of severe infectious diseases. Northern communities face the highest risk of infectious diseases brought by visitors (fly in / fly out workers, tourists [6].

The Arctic regions are especially vulnerable to biohazards because of massive seasonal trans-border and interregional migration of wildlife, which includes more than 250 migratory species. Many of these animals are also a part of traditional diets of Arctic indigenous populations (e.g., ducks, geese, swans, bird eggs, salmon, freshwater eels, marine mammals, and reindeer). Some of these species migrate up to 5,000 km annually as vertical migration from south to north and backward. Still, there is also a latitudinal form of migration, in particular, of wild swans and commercial marine fish[1] [7–9]. Wild birds are established to be able to transmit vectors of 20 zoonotic diseases into the Russian Arctic (Table 1).

Seasonal migration into the Arctic is a unique phenomenon of earthly nature. Twice a year, billions of birds fly long distances around the world and many species migrate along broadly similar, well-established routes known as flyways. Birds are the main reservoir and carrier of some parasites, as well as respiratory viruses, tick-borne encephalitis, Lyme disease, tularemia, etc. Huge populations of coastal birds, half of which breed in the Arctic, are asymptomatic carriers of all types and combinations of the influenza "A" virus neuraminidase. Strains of avian flu and coronaviruses can undergo genetic recombination with strains that affect humans [10, 11].

Table 1

Zoonotic infectious diseases that can be transferred to humans from migrating game birds in northern areas

No.	Disease	ICD-10 code	Pathogen descriptor
1	Other diseases caused by chlamydiae	A74	*Chlamidia psittaci*
2	Other salmonella infections	A.02	*Salmonella spp.*
3	Campylobacter enteritis	A04.5	*Campilobacter jejuni*
4	Enteritis and Extraintestinal yersiniosis	A04.8, A28.2	*Yersisnia pseudotuberculosis*, *Y. enterocolitica*
5	Extraintestinal yersiniosis	B30.8	*Avian paramyxovirus type 1.*
6	Newcastle conjunctivitis	J09. X	*Influenza A virus subtype H5N1*
7	Influenza due to identified zoonotic or pandemic influenza virus	A15.0	*Micobacterium avium*
8	Tuberculosis	A04	*Esherichia coli*
9	Other bacterial intestinal infections	A32.9	*Listeria monocitogenes*
10	Listeriosis	J09	*Orthomyxovirus*
11	Influenza A	B58.9	*Toxoplasma gondii*
12	Toxoplasmosis	A07. 2	*Cryptosporidium spp.*
13	Cryptosporidiosis	A07.1	*Giardia spp.*
14	Lambliasis	A28.0	*Pasteurella spp.*
15	Pasteurellosis	B96.5	*Pseudomonas spp*
16	Diseases caused by blue pus bacilli	B44.9	*Aspergillus fumigatus*
17	Aspergillosis	B39.9	*Histoplasma capsulatum*
18	Histoplasmosis	B45	*Criptococcus neoformans*
19	Cryptococcosis	B75	*Trichinella nativa*

[1] Wild Birds and Avian Influenza. An introduction to applied field research and disease sampling techniques: FAO Animal Production and Health Manual No. 5. In: D. Whitworth, S.H. Newman, T. Mundkur, P. Harris eds. *Food and Agriculture Organization of the United Nations*, 2007, 123 p.

Table 2

Human infectious diseases associated with birds and fur-bearing animals carrying infected ticks and mosquitos in the Russian Arctic

No.	Disease	ICD-10 code	Ectoparasite descriptor
1	Central European tick-borne encephalitis	A84.1	*Flavivirus arthropod-borne viruses Orthobunyavirus*
2	Lyme disease (borreliosis)	A69.2	*Borrelia burgdorferi, Borrelia garinii, Borrelia afzelii*
3	Tularemia	A21	*Francisella tularensis*
4	Mosquito-borne viral encephalitis	A83	*Alphavirus, flavivirus, bunyavirus*

Table 3

Bacterial zoonotic infections transmitted to humans through fish and other sea foods in the Russian Arctic

No.	Diseases	ICD-10 code	Pathogen descriptor
1	Cutaneous mycobacterial infection	A31.1	*Mycobacterium marinum, M. fortuitum, M. chelonei*
2	Erysipeloid	A26	*Erysipelothrix rhusiopathiae*
3	Other bacterial intestinal infections	A04.	*Campylobacter bacterium Vibrio, Edwardsiella, Escherichia coli*
4	Salmonella enteritis	A02	*Salmonella typhimurium*
5	Streptococcal and enterococcal infection	A49.1	*Streptococcus iniae*
6	Listeriosis, unspecified	A32.9	*Listeria monocytogenes*
7	Pneumonia	J15. 0	*Klebsiella pneumoniae*

As estimated, there are between 75,000 and 300,000 helminth species parasitizing vertebrates [12]. Wild bird species can absorb pathogens such as *Salmonella*, *Campylobacter*, and *Mycobacterium avium* and spread these pathogens to humans directly or through infecting poultry, including drug-resistant forms of these pathogens resulting from widespread use of antibiotics in poultry farming [13–15]. More than 40 parasitic species live on birds, in their nests, or in places where they camp. They are associated with spread of several hundred viral, bacterial, and parasitic agents. Such diseases reported in the Russian Arctic include encephalitis, smallpox, meningitis, and many other diseases (Tables 1 and 2).

Ongoing and expected climate changes aggravate the problem since they affect migration routes, seasonality, and breeding areas of insects, fish, birds, and mammals. For instance, birds frequently carry such pathogens as endoparasites like *Toxoplasma gondii*, and also ectoparasites like ticks and fleas, viruses such as tick-borne encephalitis and influenza, and bacteria causing Lyme disease and tularemia, to name but a few.

Wild migratory fish can transmit a range of parasites to humans such as roundworms (nematodes), flatworms or flukes (trematodes) and tapeworms (cestodes) as well as some bacteria (*Listeria, Aeromonas hydrophila, Campylobacter bacterium Vibrio, Edwardsiella, Escherichia coli, Salmonella typhimurium, Streptococcus iniae* and *Klebsiella pneumonia*) [16, 17] (Tables 3 and 4).

Arctic-breeding migratory animals constitute an important component of Arctic's traditional diets and thus may simultaneously be a source of human exposure to bio-accumulative environmental pollutants and pathogens. To accurately define biosecurity risk factors, specific groups of transmissible bio-associated contaminants should be identified, e.g., metals, pesticides, pharmaceuticals that can accumulate, magnify, or modify their hazardous effects through biological pathways, particularly food chains. A better insight into wild bird and fish migration patterns and transmissible infectious diseases can help predict and mitigate future outbreaks and epidemics.

Human health risks caused by biohazard vary greatly depending on its origin and exposure pathways. Transmission occurs through inhaling airborne particles, vector-borne virulent exposure, consumption of contaminated food and water, and contact with wild and domesticated animals (dogs, reindeer, or contaminated surfaces are most common in the Russian Arctic) (Tables 5 and 6).

The focus on newly emerging and climate-sensitive infections in the Arctic has grown over the past ten years. This applies to

Table 4

Parasitic diseases transmitted from fish to humans and animals

No.	Disease	ICD-10 code	Pathogen descriptor	Reservoir host
1	Diphyllobothriasis	B70.0	*Diphyllobothrium latum*	Fresh water fish
2	Opisthorchis	B66.0	*Opisthorchis felineus*	Fresh water fish
3	Anisacidosis	B81.0	*Anisakidae family*	Sea food
4	Metagonimosis	B66.8	*Metagonimus yokogawai*	Fresh water fish
5	Nanophyetiasis*	B66.8	*Nanophyetus schikhobalowi*	Fresh and sea water fish
6	Dioctophimosis*	B83.9	*Dioctophyme renale*	Fresh and sea water fish

Note: * means a species is potentially invasive for the Pacific coastal population in the Arctic.

Table 5

Zoonotic infectious diseases that can be transmitted to humans from wild vertebrates in the Russian Arctic

No.	Disease	ICD-10 code	Pathogen descriptor	Reservoir host
1	Rabies (hydrophobia)	A82.9	*Rabies lyssavirus*	Arctic foxes and wolves
2	Brucellosis	A23. 9	*Brucella abortus, B.suis*	Ungulates, foxes and bears
3	Echinococcus multilocularis infection, unspecified	B67.7	*Echinococcus multilocularis*	Arctic foxes and rodents

Table 6

Zoonotic infectious diseases that can be transmitted to humans from domesticated and semi-domesticated animals in the Russian Arctic

No.	Disease	ICD-10 code	Pathogen descriptor
1	Other bacterial infections of unspecified site	A49.8	*Capnocytophaga canimorsus*
2	Campylobacter enteritis	A04.5	*Campylobacter jejuni*
3	Tuberculosis	A15.0	*Micobacterium*
4	Listeriosis	A32.9	*Listeria monocitogenes*
5	Acute gastroenteropathy due to Norovirus	A08.1	*Norovirus*
6	Dermatophytosis, unspecified	B35.9	*Trichophyton, Microsporum и Epidermophyton.*
7	Giardiasis [lambliasis]	A07.1	*Giardia duodenalis (also known as G. lamblia and G. intestinalis)*
8	Toxocariasis [visceral Larva migrans]	B83.0	*Toxocara canis*
9	Echinococcosis, other and unspecified	B67.9	*Echinococcus*
10	Brucellosis	A23. 9	*Brucella abortus, Brucella canis melitensis, Drucella suis*
11	Dipylidiasis	B71.1	*Dipylidium caninum*
12	Scabies	B86	*Sarcoptes scabiei*
13	Fascioliasis	B66. 3	*Fasciola hepatica*

zoonotic disease networks and research initiatives like an early warning system for climate sensitive infections [18, 19].

The focus on newly emerging and climate-sensitive infections in the Arctic has grown over the past ten years. This applies to zoonotic disease networks and research initiatives like an early warning system for climate sensitive infections [18, 19].

Infectious disease rates are highly variable across the Arctic depending on a country, disease, age, sex, and location. Yet, improved sanitation, availability of qualified health care, vaccinations, and education have reduced infectious disease rates and health disparities between indigenous and non-indigenous populations across the Arctic. Infections such as tick-borne diseases (e.g., encephalitis and borreliosis), tularemia, anthrax, vibriosis, brucellosis, rabies, insect-borne diseases (e.g., bluetongue), and the infections fascioliasis and echinococcosis, which are relevant for humans and/or animals living in northern regions, have reduced considerably [20].

Climate change and biological risks. The Arctic is warming because of climate change and the temperature there is rising up to four times faster than the global average [21]. Ongoing and expected climate changes are the most significant factors making the problem truly relevant. These changes can affect geography of migration routes, seasonality, and spawning areas of wild birds, fish, insects, and animals.

The Arctic regions are at higher risk of climate change affecting transmission patterns of zoonotic and vector-borne infectious diseases. Permafrost lands represent 2/3 of the Russian territory and 11 million of the Russian population reside in the Arctic region. Russia, being the largest country in both the total Arctic area and Arctic population, is of special concern in terms of climate change-related biological risks [22–25].

Fast-thawing permafrost is a pressing Arctic-specific phenomenon that may release a range of bacterial spores and viruses preserved in frozen ground. As reported, the climate warming can cause remobilization of viable (Paleo) pathogens and biological toxins from old waste sites and buried carcasses such as the spore-forming bacterium *Bacillus anthracis*, *Variola virus* (smallpox), *Mycobacterium tuberculosis* and other revivable pathogenic viruses, spores, and fungi with extremely long viability (up to 30,000 years) [26–29].

Climatic changes may also benefit free-living bacteria and parasites whose survival and development are limited by temperature. To appropriately address emergency issues, there is a need for better integration among agencies and organizations responsible for monitoring zoonotic diseases and other biological risk factors.

Because of natural disasters (tsunamis, typhoons, flooding, and others), a few million tons of contaminated waste are washed into the oceans every year from the southern coastal regions, including persistent bacteria and viruses, parasites, and other biohazards capable of being transferred thousands of kilometers away. As estimated, the earthquake and tsunami on March 11, 2011, washed-out 5 million tons of debris in a single event. The increase in debris influx to surveyed North American and Hawaiian shorelines was substantial representing a 10-time increase over the baseline [30].

Other Arctic biohazards for humans. Microscopic algae and aquatic bacteria can also pose great threats to human health because of their ability to produce marine toxins (MTs). The most reported MTs include paralytic, amnesic, and diarrheal shellfish toxins, cyclic imines, ciguatoxin, azaspiracids, paly toxin, tetrodotoxins, and their analogs, which can lead to severe and fatal outcomes since these seafood products are a significant component in diets typical for coastal human populations [31].

Annually up to 125,000 deaths and 400,000 amputations and other severe health outcomes are registered globally. This includes infectious diseases due to animal attacks [32]. In Russia, according to long-term observations, approximately 400,000 thousand people bitten by animals apply for medical aid and 38.87 % of them get bitten by wild animals (foxes, bats, hedgehogs, badgers, and wolves)[2].

In the Arctic regions, the highest rates of appeal for medical care are observed in the Republic of Sakha-Yakutia and the Yamal-Nenets District (29.4 and 24.6 per 10 thousand inhabitants, respectively). It is necessary to pay more attention to prevention of human injuries, morbidities, and fatalities resulting from wildlife in the Arctic biosecurity policy.

Lack of threat prevention and ineffective security policy means that there are risks associated not only with uncontrolled spread of pathogens by natural pathways (e.g., because of natural disasters) but also with possible deliberate actions (known as bioterrorism).

Factors affecting the risk of spread and human resistance to infections. General approaches were suggested to explain prevalence of infectious diseases for a region as a function of several factors including the immunization rate for vaccine-preventable infectious diseases, access to safe water and food, prevalence of human immunodeficiency virus, availability of qualified health care and personal susceptibility such as age, sex and genetics[3].

Malnutrition as a nutritional status of infected people is an important factor significantly influencing human susceptibility to infectious diseases, the severity of their clinical course and outcomes. As reported, deficiency of vitamin D or selenium might decrease the immune defenses against COVID-19 and cause progression to severe disease [33, 34].

Prevention and control of micronutrient deficiencies, particularly iron, iodine, selenium, zinc, vitamin A, C, and D, which are highly prevalent in the permanent population of the Russian Arctic [35–38], should be considered an effective measure of counteraction to socioeconomic losses associated with transmissible zoonotic diseases in the Arctic.

Another point of biosecurity interest is the long period of extreme cold weather in the Russian Arctic regions at a mean daily temperature below -10 °C (up to 9 months)[4]. Cold exposure and low humidity pose a higher risk of incidence, severity of clinical course, and outcomes of respiratory tract infections [39, 40]. The Arctic-breeding migratory birds and fish, constituting a very important part of the Arctic traditional diet, may well have been a vector and source of human exposure to bioaccumulative environmental pollutants and pathogens simultaneously. Many of those pollutants, such as lead, mercury, arsenic, DDTs, and PCBs, are known to be able to affect the immune system, which leads to suppressed human resistance against virulent pathogens[5] [41, 42]. However, socioeconomic effects of human exposure to pathogens and toxins that can accumulate in food webs and spread through the same biological pathways have not been properly assessed yet.

Infectious diseases exert significant selective genetic pressure and the genes involved in the immune response are exquisitely diverse [43]. These observations suggest a powerful role of host genetic variability in susceptibility to exogenous pathogens. Prevalence of such diseases for a region is a function of factors like the immunization rate for infectious diseases that can be prevented

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[2] Animal bites. *WHO*, 2024. Available at: https://www.who.int/news-room/fact-sheets/detail/animal-bites (August 19, 2024).

[3] Rekomendatsii grazhdanam: Profilaktika beshenstva [Recommendations to citizens: Hydrophobia prevention]. *The RF Federal Service for Surveillance over Consumer Rights Protection and Human Wellbeing: official web-site*, 2021. Available at: https://www.rospotrebnadzor.ru/activities/recommendations/details.php?ELEMENT_ID=20827 (August 19, 2024) (in Russian).

[4] Climate in Siberia. Average weather, temperature, rainfall, sunshine. *Climates to travel: World climate guide*, 2023. Available at: https://www.climatestotravel.com/climate/siberia (July 11, 2024).

[5] The capacity of toxic agents to compromise the immune system (biologic markers of immunosuppression). In book: *Biological Markers in Immunotoxicology*. Washington (DC), National Academies Press (US) Publ., 1992, pp. 63–82. DOI: 10.17226/1591

by vaccines, access to safe water and food, comorbidity of immunosuppressing infections such as HIV, availability of qualified healthcare, and personal susceptibility risk factors like age, sex, and genetics.

The risk-oriented approach to mitigating health effects associated with human exposure to Arctic biohazards is still underdeveloped. Schematically, such an approach is suggested in Table 7, which summarizes the most important socio-demographic, healthcare, and environmental characteristics increasing population vulnerability and the most vulnerable groups to infections and other biohazards.

Conclusions and recommendations. The following well-known phenomena, proven facts and systemic problems are the basis for future studies of biological risk assessment:

- Paradoxical is the fact that some parasites do not die when migratory birds leave a certain area; ticks and other insect vectors are looking for a new "host", often humans or pets.
- As for wild migratory fish, they can transmit a range of parasites to humans, such as roundworms (nematodes), flatworms or flukes (trematodes), and tapeworms (cestodes), as well as some bacteria. Opisthorchiasis is the most prevalent parasitic disease spread by fish in the Russian Arctic [44]. But the natural focal infection of listeriosis is the most severe and damaging, even fatal[6]. It is an important food-borne zoonosis caused by *Listeria monocytogenes*, an intracellular pathogen with the unique potential to spread from cell to cell, thereby crossing blood-brain, intestinal, and placental barriers.
- Shellfish, such as oysters, mussels, and clams, are capable of bioaccumulating some viral pathogens from polluted waters. Consumption of contaminated shellfish can cause gastroenteritis, respiratory illness, fever, and viral hepatitis A and E [45].
- There have been comparatively few biological invasions of Arctic waters. These regions exhibit difficult environmental conditions for both native and non-native species due to their geographical isolation, cold waters, and presence of sea ice. However, the observed and expected rise in water temperatures resulting in sea ice melt because of climate change may increase the possibility of invasive species that are not native to Arctic waters [46].
- Migratory birds, fish, and animals may have significantly contributed to the global spread and pandemics of infectious diseases. A better insight into wild bird and fish migration patterns and transmissible infectious diseases can help predict future outbreaks and epidemics. Currently, various agencies and

Table 7

Human susceptibility to biological risk factors and the most vulnerable population groups

No.	Factors and conditions that increase biological risk levels
1	A disease has a higher lethality coefficient
2	Qualified healthcare including vaccination is unavailable or limited
3	Exposure to factors that affect the immune system (chemical, physical, biological, pharmaceutical) and stress
4	Micronutrient deficiency (for example vitamins A, C, D, omega-3 fatty acids, iron, iodine and zinc)
5	High population density
6	A higher proportion of the most vulnerable age groups (> 65 and < 5 years)
7	High poverty and unemployment rates
8	Pregnant women and nursing mothers
9	People with chronic non-communicable diseases or immunosuppressive states

[6] Listeriosis. *WHO*, 2018. Available at: https://www.who.int/news-room/fact-sheets/detail/listeriosis (July 05, 2024).

organizations authorized to monitor zoonotic diseases and other biohazards are not sufficiently integrated to address emergency issues. Experience gained through the ongoing pandemic of SARS-CoV-2 shows that information on regional and global transmission risks of highly virulent infections to humans appears to be incomplete or is not readily available. A methodology for assessing and predicting risks of spreading virulent pathogens in the Arctic has not been sufficiently developed so far. Existing measures to control infections are mostly focused on human-to-human transmission.

- Obviously, there is a high societal demand to develop an Arctic biosecurity policy considering interactive effects of environmental multi-hazard exposures (chemical, physical, dietary, and infectious), which are spread through region-specific biological pathways.

Following the knowledge gaps and challenges identified from the critical review and analyses of published information sources, it is necessary to propose recommendations for improving the biosecurity system in the Arctic regions:

a. Transmission risks of infectious diseases related to human mobility in the Arctic. To develop a system for surveillance and mechanisms of communication and support for more prompt and effective reactions to people coming from other regions where infectious outbreaks have been detected including 1) immigration and job-related circulation (fly-in / fly-out workers); 2) Arctic tourism; 3) traditional harvesting activities, nomadic lifestyles, rituals, and other human mobility drivers [47].

b. Prediction of biological risk events. There have been several attempts to develop predictive models that describe how zoonotic diseases occur and how fast they spread. The key risk factors at the national level that may predict three types of illnesses have been identified: 1) existing zoonotic diseases: land area, human population density, and area of forest; 2) emerging diseases: land area, human population density, and the human development index; 3) human diseases: high health expenditure per capita, mean annual temperature, land area, human population density, human development index, and precipitations [48]. In this study, the majority of Arctic nations were categorized as having minimal likelihood of spread of infectious diseases as regards these risk factors.

Considering various biohazard exposures that residents of the Arctic may encounter, it would make sense to evaluate the overall population risk associated with all recognized biological factors. A model for similar cases has also been suggested in the environmental methodology [49].

We have slightly modified the quantitative equation to adapt its description of probabilities, risk factors, and human vulnerability for multifactorial biohazard events (Equation 1):

$$Risk = \sum\left(\int_0^1 P_{(T|HE)} \cdot \sum\left(P_{(S|HE)} \cdot \left(N_{(ER|HE)} \cdot V_{(ER|HE)}\right)\right)\right),$$

where $P_{(T|HE)}$ is the temporal probability of a certain biohazard exposure event (HE), such as occurrence of endemic, re-emerging, and emerging zoonotic and vector-borne diseases, allergies, or an increase in a exposure to chemical bioaccumulated in food chains up to the level of toxicity;

$P_{(S|HE)}$ is the spatial probability that a particular populated area is affected by a certain biohazard event;

$N_{(ER|HE)}$ is the number of people at risk (the number of people who can be infected directly through natural reservoirs or indirectly through contact with intermediate hosts);

$V_{(ER|HE)}$ is the vulnerability of population at risk to a biohazard exposure (as a value between 0 and 1 for each determinant of risk).

c. Additional measures to update the Arctic biosecurity policy and practices. Additional measures on providing biosecurity in the

Table 8

Qualitative biological risk assessment and basic management counteractions

Risk level/impact	Expected counteractions
Very low	Biological risk is frequently judged acceptable. If appropriate, a possibility should be considered to perform monitoring of relevant risk groups.
Low	Escalation should be taken into consideration while quickly reviewing countermeasures to mitigate biological risk. It is necessary to inform appropriate public authorities and municipal bodies about the risk and suggest relevant protection measures for the most vulnerable population groups.
Moderate	Escalation should be taken into consideration while quickly reviewing countermeasures to mitigate biological risk. It is necessary to inform appropriate public authorities and municipal bodies about the risk and suggest relevant protection measures for the most vulnerable population groups.
High	Immediate countermeasures are mandatory as well as creation of interdepartmental groups on biohazard prevention and communication about the risk to appropriate public agencies. It is mandatory to perform daily monitoring of risks and to provide medical observation of the total population living in a risk-exposed area.
Very high	A state of public healthcare emergency. To lessen the effects and/or prevent the catastrophic development of biological risk events, it is necessary to take immediate measures stipulated in the legislation that regulates public relations under emergencies.

Arctic should include the following specific products, services and approaches to assessing and preventing biological risks:

– A standards-based conceptual model of and integrated data system to support the Arctic biosecurity policy;

– Integration of a biosecurity incident reporting system into the context of Arctic public healthcare practices;

– Risk prediction model for biohazard-related chronic diseases and other health effects of high public importance for the Arctic population;

– Human health risk stratification system for Arctic biohazards;

– Framework for assessing sustainability of public healthcare systems considering potential pandemic or epidemic risks and exposure to biotoxins;

– Implementation of biosecurity indicators and health ranking criteria enabling quantification of public healthcare protection against biological hazards into the Arctic policy;

– Development of a risk stratification system addressing specific population management challenges and matching biological risk with levels of care;

– Implementation of international systems for monitoring, predicting, and managing health risks associated with spread of highly virulent pathogens, parasites, and other biological hazards across the Arctic;

– A community-based information system for biosecurity;

– Educational and training programs for health care providers.

Recommendations on risk manageemnt for biohazards are presented in the Table 8.

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References

1. Woolhouse M.E., Gowtage-Sequeria S. Host range and emerging and reemerging pathogens. *Emerg. Infect. Dis.*, 2005, vol. 11, no. 12, pp. 1842–1847. DOI: 10.3201/eid1112.050997

2. Jones K.E., Patel N.G., Levy M.A., Storeygard A., Balk D., Gittleman J.L., Daszak P. Global trends in emerging infectious diseases. *Nature*, 2008, vol. 451, no. 7181, pp. 990–993. DOI: 10.1038/nature06536

3. GBD 2015 Mortality and Causes of Death Collaborators. Global, regional, and national life expectancy, all-cause mortality, and cause-specific mortality for 249 causes of death, 1980–2015: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet*, 2016, vol. 388, no. 10053, pp. 1459–1544. DOI: 10.1016/S0140-6736(16)31012-1

4. Global Burden of Disease Collaborative Network. Global Burden of Disease Study 2015 (GBD 2015) Life Expectancy, All-Cause and Cause-Specific Mortality 1980–2015. Seattle, USA, Institute for Health Metrics and Evaluation (IHME), 2016. Available at: https://ghdx.healthdata.org/record/ihme-data/gbd-2015-life-expectancy-all-cause-and-cause-specific-mortality-1980-2015 (October 11, 2024).

5. Gebreyes W.A., Dupouy-Camet J., Newport M.J., Oliveira C.J.B., Schlesinger L.S., Saif Y.M., Kariuki S., Saif L.J. [et al.]. The Global One Health Paradigm: Challenges and Opportunities for Tackling Infectious Diseases at the Human, Animal, and Environment Interface in Low-Resource Settings. *PLoS Negl. Trop. Dis.*, 2014, vol. 8, no. 11, pp. e3257. DOI: 10.1371/journal.pntd.0003257

6. Keatts L.O., Robards M., Olson S.H., Hueffer K., Insle S.J., Joly D.O., Kutz S., Lee D.S. [et al.]. Implications of zoonoses from hunting and use of wildlife in North American Arctic and boreal biomes: pandemic potential, monitoring, and mitigation. *Front. Public Health*, 2021, vol. 9, pp. 627–654. DOI: 10.3389/fpubh.2021.627654

7. Duijns S., Jukema J., Spaans B., van Horssen P., Piersma T. Revisiting the proposed leapfrog migration of bar-tailed godwits along the East-Atlantic Flyway. *Ardea*, 2012, vol. 100, no. 1, pp. 37–43. DOI: 10.5253/078.100.0107

8. Parkinson A.J., Evengard B., Semenza J.C., Ogden N., Børresen M.L., Berner J., Brubaker M., Sjöstedt A. [et al.]. Climate change and infectious diseases in the Arctic: establishment of a circumpolar working group. *Int. J. Circumpolar Health*, 2014, vol. 73, pp. 25163. DOI: 10.3402/ijch.v73.25163

9. Varpe Ø., Bauer S. Seasonal Animal Migrations and the Arctic: Ecology, Diversity, and Spread of Infectious Agents. In book: *Arctic One Health. Challenges for Northern Animals and People*; M. Tryland ed. Springer, Cham, 2022, pp. 47–76. DOI: 10.1007/978-3-030-87853-5_3

10. AbuBakar U., Amrani L., Kamarulzaman F.A., Karsani S.A., Hassandarvish P., Khairat J.E. Avian influenza virus tropism in humans. *Viruses*, 2023, vol. 15, no. 4, pp. 833. DOI: 10.3390/v15040833

11. Su S., Wong G., Shi W., Liu J., Lai A.C.K., Zhou J., Liu W., Bi Y., Gao G.F. Epidemiology, genetic recombination, and pathogenesis of coronaviruses. *Trends Microbiol.*, 2016, vol. 24, no. 6, pp. 490–502. DOI: 10.1016/j.tim.2016.03.003

12. Dobson A., Lafferty K.D., Kuris A.M., Hechinger R.F., Jetz W. Colloquium paper: homage to Linnaeus: how many parasites? How many hosts? *Proc. Natl Acad. Sci. USA*, 2008, vol. 105, suppl. 1, pp. 11482–11489. DOI: 10.1073/pnas.0803232105

13. Vogt N.A. Wild birds and zoonotic pathogens. In book: *Zoonoses: Infections Affecting Humans and Animals*; A. Sing ed. Springer, Cham, 2023, pp. 1003–1033. DOI: 10.1007/978-3-031-27164-9_47

14. Dhama K., Karthik K., Tiwari R., Shabbir M.Z., Barbuddhe S., Malik S.V.S., Singh R.K. Listeriosis in animals, its public health significance (food-borne zoonosis) and advances in diagnosis and control: a comprehensive review. *Vet. Q.*, 2015, vol. 35, no. 4, pp. 211–235. DOI: 10.1080/01652176.2015.1063023

15. Dini F.M., Graziosi G., Lupini C., Catelli E., Galuppi R. Migratory wild birds as potential long-distance transmitters of *Toxoplasma gondii* infection. *Pathogens*, 2023, vol. 12, no. 3, pp. 478. DOI: 10.3390/pathogens12030478

16. Ziarati M., Zorriehzahra M.J., Hassantabar F., Mehrabi Z., Dhawan M., Sharun K., Emran T.B., Dhama K. [et al.]. Zoonotic diseases of fish and their prevention and control. *Vet. Q.*, 2022, vol. 42, no. 1, pp. 95–118. DOI: 10.1080/01652176.2022.2080298

17. Håkonsholm F., Hetland M.A.K., Svanevik C.S., Lunestad B.T., Löhr I.H., Marathe N.P. Insights into the genetic diversity, antibiotic resistance and pathogenic potential of Klebsiella pneumoniae from the Norwegian marine environment using whole-genome analysis. *Int. J. Hyg. Environ. Health*, 2022, vol. 242, pp. 113967. DOI: 10.1016/j.ijheh.2022.113967

18. Ma Y., Destouni G., Kalantari Z., Omazic A., Evengård B., Berggren C., Thierfelder T. Linking climate and infectious disease trends in the Northern Arctic Region. *Sci. Rep.*, 2021, vol. 11, no. 1, pp. 20678. DOI: 10.1038/s41598-021-00167-z

19. Leibovici D.G., Bylund H., Björkman C., Tokarevich N., Thierfelder T., Evengård B., Quegan S. Associating land cover changes with patterns of incidences of climate-sensitive infections: an example on tick-borne diseases in the Nordic Area. *Int. J. Environ. Res. Public Health*, 2021, vol. 18, no. 20, pp. 10963. DOI: 10.3390/ijerph182010963

20. Waits A., Emelyanova A., Oksanen A., Abass K., Rautio A. Human infectious diseases and the changing climate in the Arctic. *Environ. Int.*, 2018, vol. 121, pt 1, pp. 703–713. DOI: 10.1016/j.envint.2018.09.042

21. Rantanen M., Karpechko A.Y., Lipponen A., Nordling K., Hyvärinen O., Ruosteenoja K., Vihma T., Laaksonen A. The Arctic has warmed nearly four times faster than the globe since 1979. *Commun. Earth Environ.*, 2022, vol. 3, pp. 168. DOI: 10.1038/s43247-022-00498-3

22. Smith M.I., Ke Y., Geyman E.C., Reahl J.N., Douglas M.M., Seelen E.A., Magyar J.S., Dunne K.B.J. [et al.]. Mercury stocks in discontinuous permafrost and their mobilization by river migration in the Yukon River Basin. *Environ. Res. Lett.*, 2024, vol. 19, pp. 084041. DOI: 10.1088/1748-9326/ad536e

23. Revich B., Chashchin V. Climate change impact on public health in the Russian Arctic. Moscow, United Nation in Russia, 2008, 24 p.

24. AMAP 2017. Adaptation Actions for a Changing Arctic: Perspectives from the Bering-Chukchi-Beaufort Region. Oslo, Norway, Arctic Monitoring and Assessment Programme (AMAP), 2017, 255 p. Available at: https://www.amap.no/documents/download/2993/inline (October 05, 2024).

25. Orlov D., Menshakova M., Thierfelder T., Zaika Y., Böhme S., Evengard B., Pshenichnaya N. Healthy ecosystems are a prerequisite for human health – A call for action in the era of climate change with a focus on Russia. *Int. J. Environ. Res. Public Health*, 2020, vol. 17, no. 22, pp. 8453. DOI: 10.3390/ijerph17228453

26. El-Sayed A., Kamel M. Future threat from the past. *Environ. Sci. Pollut. Res.*, 2021, vol. 28, pp. 1287–1291. DOI: 10.1007/s11356-020-11234-9

27. Wu R., Trubl G., Taş N., Jansson J.K. Permafrost as a potential pathogen reservoir. *One Earth*, 2022, vol. 5, no. 4, pp. 351–360. DOI: 10.1016/j.oneear.2022.03.010

28. Alempic J.-M., Lartigue A., Goncharov A.E., Grosse G., Strauss J., Tikhonov A.N., Fedorov A.N., Poirot O. [et al.]. An Update on Eukaryotic viruses revived from ancient permafrost. *Viruses*, 2023, vol. 15, no. 2, pp. 564. DOI: 10.3390/v15020564

29. Revich B.A., Shaposhnikov D.A., Raichich S.R., Saburova S.A., Simonova E.G. Creating zones in administrative districts located in the russian arctic region specific as per threats of cattle burials decay due to permafrost degradation. *Health Risk Analysis*, 2021, no. 1, pp. 115–125. DOI: 10.21668/health.risk/2021.1.12.eng

30. Murray C.C., Maximenko N., Lippiattde S. The influx of marine debris from the Great Japan Tsunami of 2011 to North American shorelines. *Mar. Pollut. Bull.*, 2018, vol. 132, pp. 26–32. DOI: 10.1016/j.marpolbul.2018.01.004

31. Silva M., Pratheepa V.K., Botana L.M.,Vasconcelos V. Emergent toxins in North Atlantic temperate waters: a challenge for monitoring programs and legislation. *Toxins (Basel)*, 2015, vol. 7, no. 3, pp. 859–885. DOI: 10.3390/toxins7030859

32. Tryphonas H. Approaches to detecting immunotoxic effects of environmental contaminants in humans. *Environ. Health Perspect.*, 2001, vol. 109, suppl. 6, pp. 877–884. DOI: 10.1289/ehp.01109s6877

33. Terekhov P.A., Rybakova A.A., Terekhova M.A., Troshina E.A. Awareness of the population in Russian Federation about iodine deficiency, its effects and methods for prevention of iodine deficiency disorders. *Klinicheskaya i eksperimental'naya tireoidologiya*, 2019, vol. 15, no. 3, pp. 118–123. DOI: 10.14341/ket12239 (in Russian).

34. Im J.H., Je Y.S., Baek J., Chung M.-H., Kwon H.Y., Lee J.-S. Nutritional status of patients with COVID-19. *Int. J. Infect. Dis.*, 2020, vol. 100, pp. 390–393. DOI: 10.1016/j.ijid.2020.08.018

35. Kaya M.O., Pamukçu E., Yakar B. The role of vitamin D deficiency on COVID-19: a systematic review and meta-analysis of observational studies. *Epidemiol. Health*, 2021, vol. 43, pp. e2021074. DOI: 10.4178/epih.e2021074

36. Bakaeva E.A., Eremeyshvili A.V. Contents of some trace elements in biosubstrates of preschool children of Northern European in Russia. *Ekologiya cheloveka*, 2016, vol. 23, no. 4, pp. 26–31. DOI: 10.33396/1728-0869-2016-4-26-31 (in Russian).

37. Artemenkov A.A. The problem of the prevention of endemic human diseases and microelementoses. *Profilakticheskaya meditsina*, 2019, vol. 22, no. 3, pp. 92–100. DOI: 10.17116/profmed 20192203192 (in Russian).

38. Sorokina T., Sobolev N., Belova N., Aksenov A., Kotsur D., Trofimova A., Varakina Y., Grjibovski A.M. [et al.]. Diet and Blood Concentrations of Essential and Non-Essential Elements among Rural Residents in Arctic Russia. *Nutrients*, 2022, vol. 14, no. 23, pp. 5005. DOI: 10.3390/nu14235005

39. Mourtzoukou E.G., Falagas M.E. Exposure to cold and respiratory tract infections. *Int. J. Tuberc. Lung Dis.*, 2007, vol. 11, no. 9, pp. 938–943.

40. Mäkinen T.M., Juvonen R., Jokelainen J., Harju T.H., Peitso A., Bloigu A., Silvennoinen-Kassinen S., Leinonen M., Hassi J. Cold temperature and low humidity are associated with increased occurrence of respiratory tract infections. *Respir. Med.*, 2009, vol. 103, no. 3, pp. 456–462. DOI: 10.1016/j.rmed.2008.09.011

41. Ross P.S. The role of immunotoxic environmental contaminants in facilitating the emergence of infectious diseases in marine mammals. *Human and Ecological Risk Assessment: An International Journal*, 2002, vol. 8, no. 2, pp. 277–292. DOI: 10.1080/20028091056917

42. Kataoka C., Kashiwada S. Ecological risks due to immunotoxicological effects on aquatic organisms. *Int. J. Mol. Sci.*, 2021, vol. 22, no. 15, pp. 8305. DOI: 10.3390/ijms22158305

43. Burgner D., Jamieson S.E., Blackwell J.M. Genetic susceptibility to infectious diseases: big is beautiful, but will bigger be even better? *Lancet Infect. Dis.*, 2006, vol. 6, no. 10, pp. 653–663. DOI: 10.1016/S1473-3099(06)70601-6

44. Fedorova O.S., Kovshirina Y.V., Kovshirina A.E., Fedotova M.M., Deev I.A., Petrovskiy F.I., Filimonov A.V., Dmitrieva A.I. [et al.]. Analysis of Opisthorchis felineus infection and liver and intrahepatic bile ducts cancer incidence rate in Russian Federation. *Byulleten' sibirskoi meditsiny*, 2016, vol. 15, no. 5, pp. 147–158. DOI: 10.20538/1682-0363-2016-5-147-158 (in Russian).

45. Shuping L.S., Human I.S., Lues J.F.R., Paulse A.N. The prevalence of viruses related to the production of mussels and oysters in Saldanha Bay: a systematic review. *Aquac. J.*, 2023, vol. 3, no. 2, pp. 90–106. DOI: 10.3390/aquacj3020009

46. Bluhm B.A., Gebruk A.V., Gradinger R., Hopcroft R.R., Huettmann F., Kosobokova K.N., Sirenko B.I., Weslawski J.M. Arctic marine biodiversity: an update of species richness and examples of biodiversity change. *Oceanography*, 2011, vol. 24, no. 3, pp. 232–248. DOI: 10.5670/oceanog.2011.75

47. Wang L., Wang X. Influence of temporary migration on the transmission of infectious diseases in a migrants' home village. *J. Theor. Biol.*, 2012, vol. 300, pp. 100–109. DOI: 10.1016/j.jtbi.2012.01.004

48. Singh B.B., Ward M.P., Dhand N.K. Geodemography, environment and societal characteristics drive the global diversity of emerging, zoonotic and human pathogens. *Transbound. Emerg. Dis*., 2022, vol. 69, no. 3, pp. 1131–1143. DOI: 10.1111/tbed.14072

49. Van Westen C.J., Greiving S. Multi-hazard risk assessment and decision making. In book: *Environmental hazards methodologies for risk assessment and management*; N.R. Dalezios ed. London, IWA Publ., 2017, pp. 31–94. DOI: 10.2166/9781780407135_0031

Chashchin V.P., Zaitseva N.V., Chashchin M.V., Sobolev N.A., Sorokina T.Yu., Shakirov M.M. Biological risk factors in the Russian Arctic: a scoping literature review. Health Risk Analysis, 2024, no. 4, pp. 160–173. DOI: 10.21668/health.risk/2024.4.14.eng

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