
Blast from the Past: Pathogen Release from Thawing Permafrost could lead to Future Pandemics

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ABSTRACT

Some viruses and bacteria can survive freezing for thousands of years. Permafrost (ground with a temperature of or below 0°C for at least two consecutive years) covers 25% of the Northern Hemisphere. Whilst permafrost has persisted for millions of years, it is now thawing rapidly because of global warming. When permafrost thaws, microorganisms that were previously dormant can be released and become active. Some microorganisms may be pathogens, which can infect and potentially cause severe disease in humans, animals, and plants with major impacts on public health, socioeconomic wellbeing, and natural ecosystems. Global warming and increased disturbance of permafrost from human activities in the Arctic Circle are raising the likelihood of future localised outbreaks, or even pandemics, from dormant pathogens hidden in these frozen soils. This article provides a background to the risks associated with the release of pathogens from permafrost, how these risks can be minimised, and the implications for policy and international cooperation in light of the Covid-19 pandemic.

SCIENCE ⇒ POLICY

Global warming is increasing the chance that disease-causing microbes will emerge from frozen soils called permafrost. Thawing permafrost releases dormant viruses and bacteria which can cause serious disease outbreaks. Global cooperation and surveillance at sites of mass graves and past outbreaks are needed to manage this threat to public health.

Keywords pandemic · permafrost · pathogens · climate change

Background

The Covid-19 pandemic demonstrates the extreme risk posed by novel pathogens to human civilisation and the global need to take the risk of future pandemics more seriously. The SARS-CoV-2 virus is thought to have been transmitted to humans in an animal market and ultimately from natural reservoirs of various pathogens that circulate within different animal populations [1–3]. A less commonly recognised source of novel pathogens comes from an unlikely source: permafrost [4–7].

Permafrost is defined as any ground that exists at a temperature of or below 0°C for at least two consecutive years [8]. It typically consists of soil held together by ice; this unique environment may harbour novel pathogens that have effectively been frozen in time. Permafrost underlies a substantial proportion of the Earth's surface: 25% of the Northern Hemisphere and 17% of the Earth's exposed land surface [9]. Given its temperature-based definition, this permafrost layer is highly susceptible to global warming caused by climate change, which may expose much of its organic contents [8, 10–15]. Portions of the permafrost routinely thaw each summer, but permafrost has warmed globally by 0.29°C (+0.12) from 2007–2016 [8] and it is expected that ancient permafrost layers buried deeper in the ground will continue to be exposed.

Pathogens, such as viruses and bacteria, are thought to be able to survive in frozen conditions for thousands of years [5] and have been detected in permafrost by scientists since the late nineteenth century [4, 6, 16]. Therefore, the risk that such pathogens could be exposed by thawing permafrost as global warming increases temperatures in the polar regions is a serious one [7]: particularly because the Arctic Circle is warming approximately three times faster than the rest of the world [17, 18]. This issue was highlighted by a recent Horizon Scan for biodiversity conservation in 2018 [19]. Given the clear and present dangers of novel pathogens to public health, it is important that the risk posed by pathogens in permafrost is explored in more detail.

Previous evidence of permafrost-related pathogen transmission and infection

A BBC Earth article [20] reported on the most recent (at time of writing) and widely acknowledged transmission of a pathogen originating in the permafrost to animals and humans. In August 2016, in a remote area of the Siberian tundra called the Yamal Peninsula in the Arctic Circle, a 12-year-old boy died and at least twenty people were hospitalised after being exposed to *Bacillus anthracis*, the agent of anthrax, a common disease of livestock and occasionally of humans [20, 21]. The source was traced back to a carcass of a reindeer that had perished 75 years before. Thawing permafrost had exposed the carcass, releasing infectious *B. anthracis* spores into the water, soil, and ultimately the local food supply [20, 22]. Records also show that from 1897–1925, approximately 1.5 million deer died from anthrax in Northern Russia and currently lie buried in shallow graves due to the difficulty of digging in the tundra soils [6]. Anthrax in humans have been reported in 29,000 settlements in Northern Russia located near burial grounds of cattle that succumbed to anthrax in the past, including over 200 in settlements of the Yakutia people [6]. The threat of the re-emergence of anthrax spores remains a real and present danger given that they have been shown to remain viable for 105 years in permafrost [23]. Whilst anthrax is a serious infectious disease that causes severe illness, it is spread by spores and is not contagious [21]. It is therefore highly unlikely to cause pandemics on the scale of the recent Covid-19 pandemic, but most probably acute, local outbreaks of disease.

More concerning is the identification of pathogenic materials in the permafrost, such as fragments of RNA (ribonucleic acid – the genetic material of certain viruses) from the 1918 Spanish influenza virus in corpses from mass graves in the tundra of Alaska [24]. Fragments of viral DNA from the variola or Smallpox virus were also detected in frozen mummies unearthed in Siberia, which also had visible Smallpox-like spores [25]. Although these were only degraded fragments, it is possible that intact viruses, such as Small-

pox and other viruses that have caused past pandemics including the bubonic plague, are buried in mass graves [6]. The most likely viruses to persist in the permafrost are so-called 'giant viruses' that resist many of the pressures that burst open smaller viruses due to their rugged outer shells [16]. For example, a Pithovirus capable of replicating itself was found in 30,000-year-old thawed permafrost in Siberia (although typically only infects amoebas) [26], whilst 5,000-year-old caribou faeces was also found to contain viable virus particles [27].

Although the risk of human infection by viral pathogens hidden within the permafrost is fairly low, there are many unknowns surrounding the level of infectiousness or the disease severity associated with such viruses. Therefore, assessing different risk-based scenarios is important, including the worst-case scenario in which a highly infectious virus is released, against which most people will lack prior immunity or even cross-reactive protection from current antibodies [28].

It is also possible that fungi, another type of pathogen, are harboured in the permafrost. Whilst most fungal species have beneficial impacts (e.g., through contributing essential ecosystem services such as supporting crop production [29–31]), pathogenic fungi can have major negative impacts on human health (particularly of immunosuppressed people). Fungal pathogens also threaten wider society by infecting trees and impacting forestry production, or by infecting crops and harming global food security [32–34]. However, diseases caused by fungal species are not thought to be contagious and so have a limited potential to cause pandemics [28]. Nevertheless, the growing interconnectedness of world trade and travel means that the potential for fungal pathogens to impact forestry and crop production is a major concern (e.g., as illustrated by the spread of *Hymenoscyphus fraxineus*, the cause of ash dieback, across Europe; [35, 36]).

The most likely types of pathogens that would be able to survive in permafrost, and therefore arguably pose the greatest risk, are those that can form spores (e.g., fungal pathogens, Anthrax-causing bacterium *B.anthraxis*, and species of *Clostridium* bacteria that cause tetanus and botulism; *C.tetani* and *C.botulinum*, respectively [4, 7, 28, 32]). Given antibiotics are likely to

be the main line of defence against infection by spore-forming bacteria, we must carefully consider whether bacteria from permafrost can be effectively treated with current antibiotics. Antibiotic or antimicrobial resistance is a major growing concern for public health globally, as more and more bacteria evolve to survive exposure to multiple drugs, rendering conventional medical treatments less effective [37, 38]. It is dangerous to assume that bacteria lying dormant in permafrost have not yet evolved resistance to current antibiotics, since research has suggested that some bacteria, isolated in caves for tens of thousands of years, demonstrated resistance to over 18 modern antibiotics – most likely gained through competition with fungi that naturally produce antibiotics [39].

Future risks and policy implications

Whilst the current likelihood of the release of a contagious pathogen from permafrost is likely to be low at present, the current Covid-19 pandemic demonstrates the need to take the risk of such an occurrence seriously. Increasing levels of human contact with thawing permafrost directly driven by climate change, as well as increased oil, gas, and mineral extraction in the Arctic circle, will only increase the chance of pathogens being released from thawing permafrost. In particular, the evidence suggests that the likelihood of localised outbreaks due to spore-driven pathogens, that cause diseases such as Anthrax, is at least moderate and should be taken extremely seriously.

However, with increased preparedness, monitoring, and surveillance, the threat from such pathogens could be minimised to a great extent. For example, pre-emptive monitoring and surveillance to detect Anthrax outbreaks should be targeted towards the 13,885 cattle burial grounds scattered across northern Russia [6, 28], whilst local and historical records can be used to identify more high-risk sites in other parts of the Arctic Circle (e.g., in Scandinavia and North America). The same approach is also likely to be useful for identifying old sites of mass graves for the bubonic plague and Spanish flu using historical

records. Early monitoring and surveillance in high-risk areas could catch dangerous pathogens before they become a serious problem.

Such monitoring and surveillance should also consider human exploitation of the Arctic Circle for oil, gas, and mineral extraction, which may lead to novel pathogen exposure events. Organisations need to acknowledge the biosecurity risks involved in undertaking these activities and ensure adherence to strict biosecurity protocols, so that risk is minimised for humans in contact with permafrost soils. Ultimately, to ensure organisations are held accountable for their actions, local and international laws may need to be considered to regulate activities in the Arctic Circle from a biosecurity perspective [40–42].

Effective surveillance and monitoring for potential outbreaks will require strong cooperation between local and international public health organisations (such as the World Health Organisation (WHO)), and between governments of countries where most of the Northern Hemisphere's permafrost exists (i.e., the USA, Canada, Russia, Norway, Finland, and Sweden [40–42]). Whilst such cooperation may be challenging, the consequences of being unprepared to contain and respond to developing outbreaks of novel pathogens from permafrost could represent a serious threat for the global economy and society, as demonstrated by Covid-19. Therefore, it is in the mutual interests of all nations to cooperate in the monitoring and surveillance of novel pathogen outbreaks from permafrost.

It is also important to acknowledge that pathogens have been previously used to manufacture and test biological weapons (mostly by governments in relation to Anthrax-causing *B.anthraxis* pre- and post-World War II [43], but also more recently in a 2001 attack via letters in the US postal system [44]). Therefore, there is clearly potential for groups or organisations with malicious intent to extract and modify microorganisms frozen in permafrost for dangerous agendas and purposes [45–50], making strong international cooperation and leadership from the WHO even more important in this regard.

Ultimately, tackling the climate crisis and limiting global warming according to the Paris Agreement will help to address the major driver be-

hind permafrost thawing and potential release of pathogens. The risk posed by thawing permafrost, on top of the myriad of threats already posed by climate change, should inspire all nations to take their commitments to reduce their greenhouse gas emissions seriously.

Conclusion

The more that human civilisation extracts and exposes permafrost directly or indirectly through physical exploitation or climate change, the greater the likelihood that novel pathogens may be released and cause death and disease in human, animal and plant populations. Underestimating the threat of novel pathogens from unusual sources has been shown to carry serious consequences for all human civilisation, as demonstrated by the Covid-19 pandemic. Although the likelihood of a pandemic caused by pathogens in permafrost is relatively low compared to zoonoses (e.g., Covid-19), the risks posed by permafrost-related pathogens must be taken seriously. Creating and implementing appropriate biosecurity management plans in areas of greatest risk could save many lives and livelihoods. The effectiveness of these plans at controlling any outbreaks from permafrost will ultimately depend on strong international cooperation and regulation by public health organisations and governments.

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References

- [1] Y.-Z. Zhang and E. C. Holmes, “A genomic perspective on the origin and emergence of sars-cov-2,” *Cell*, vol. 181, no. 2, pp. 223–227, 2020. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0092867420303287>
- [2] S.-m. Jung, R. Kinoshita, R. N. Thompson, K. Hayashi, N. M. Linton, Y. Yang, A. R. Akhmetzhanov, and H. Nishiura, “Epidemiological identification of a novel infectious disease in real time: Analysis of the atypical pneumonia outbreak in wuhan, china, 2019-20,” *medRxiv*, 2020. [Online]. Available: <https://www.medrxiv.org/content/early/2020/02/03/2020.01.26.20018887>
- [3] R. Lu, X. Zhao, J. Li, P. Niu, B. Yang, H. Wu, W. Wang, H. Song, B. Huang, N. Zhu, Y. Bi, X. Ma, F. Zhan, L. Wang, T. Hu, H. Zhou, Z. Hu, W. Zhou, L. Zhao, J. Chen, Y. Meng, J. Wang, Y. Lin, J. Yuan, Z. Xie, J. Ma, W. J. Liu, D. Wang, W. Xu, E. C. Holmes, G. F. Gao, G. Wu, W. Chen, W. Shi, and W. Tan, “Genomic characterisation and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding,” *The Lancet*, vol. 395, no. 10224, pp. 565–574, 2020. [Online]. Available: <https://app.dimensions.ai/details/publication/pub.1124428749andhttp://www.thelancet.com/article/S0140673620302518/pdf>
- [4] D. A. Gilichinsky, S. Wagener, and T. A. Vishnevetskaya, “Permafrost microbiology,” *Permafrost and Periglacial Processes*, vol. 6, no. 4, pp. 281–291, 1995.
- [5] B. C. Christner, E. Mosley-Thompson, L. G. Thompson, and J. N. Reeve, “Bacterial recovery from ancient glacial ice,” *Environmental Microbiology*, vol. 5, no. 5, pp. 433–436, 2003. [Online]. Available: <https://sfamjournals.onlinelibrary.wiley.com/doi/abs/10.1046/j.1462-2920.2003.00422.x>
- [6] B. A. Revich and M. A. Podolnaya, “Thawing of permafrost may disturb historic cattle burial grounds in east siberia,” *Global Health Action*, vol. 4, no. 1, p. 8482, 2011, pMID: 22114567. [Online]. Available: <https://doi.org/10.3402/gha.v4i0.8482>
- [7] S. Houwenhuysse, E. Macke, L. Reyserhove, L. Bulteel, and E. Decaestecker, “Back to the future in a petri dish: Origin and impact of resurrected microbes in natural populations,” *Evolutionary Applications*, vol. 11, no. 1, pp. 29–41, 2018. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1111/eva.12538>
- [8] B. K. Biskaborn, S. L. Smith, J. Noetzi, H. Matthes, G. Vieira, D. A. Strelt'skiy, P. Schoeneich, V. E. Romanovsky, A. G. Lewkowicz, A. Abramov, M. Allard, J. Boike, W. L. Cable, H. H. Christiansen, R. Delaloye, B. Diekmann, D. Drozdov, B. Etzelmüller, G. Grosse, M. Guglielmin, T. Ingeman-Nielsen, K. Isaksen, M. Ishikawa, M. Johansson, H. Johannsson, A. Joo, D. Kaverin, A. Kholodov, P. Konstantinov, T. Kröger, C. Lambiel, J.-P. Lanckman, D. Luo, G. Malkova, I. Meiklejohn, N. Moskalenko, M. Oliva, M. Phillips, M. Ramos, A. B. K. Sannel, D. Sergeev, C. Seybold, P. Skryabin, A. Vasiliev, Q. Wu, K. Yoshikawa, M. Zheleznyak, and H. Lantuit, “Permafrost is warming at a global scale,” *Nature Communications*, vol. 10, no. 1, p. 264, 2019. [Online]. Available: <https://doi.org/10.1038/s41467-018-08240-4>
- [9] S. Gruber, “Derivation and analysis of a high-resolution estimate of global permafrost zonation,” *The Cryosphere*, vol. 6, no. 1, pp. 221–233, 2012. [Online]. Available: <https://tc.copernicus.org/articles/6/221/2012/>
- [10] V. E. Romanovsky, D. S. Drozdov, N. G. Oberman, G. V. Malkova, A. L. Kholodov, S. S. Marchenko, N. G. Moskalenko, D. O. Sergeev, N. G. Ukraintseva, A. A. Abramov, D. A. Gilichinsky, and A. A. Vasiliev, “Thermal state of permafrost in russia,” *Permafrost and Periglacial Processes*, vol. 21, no. 2, pp. 136–155, 2010. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/ppp.683>
- [11] V. E. Romanovsky, S. L. Smith, and H. H. Christiansen, “Permafrost thermal state in the polar northern hemisphere during the international polar year 2007–2009: a synthesis,” *Permafrost and Periglacial Processes*,

- vol. 21, no. 2, pp. 106–116, 2010. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/ppp.689>
- [12] L. Zhao, Q. Wu, S. Marchenko, and N. Sharkhuu, “Thermal state of permafrost and active layer in central asia during the international polar year,” *Permafrost and Periglacial Processes*, vol. 21, no. 2, pp. 198–207, 2010. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/ppp.688>
- [13] H. H. Christiansen, B. Etzelmüller, K. Isaksen, H. Juliussen, H. Farbrot, O. Humlum, M. Johansson, T. Ingeman-Nielsen, L. Kristensen, J. Hjort, P. Holmlund, A. B. K. Sannel, C. Sigsgaard, H. J. Åkerman, N. Foged, L. H. Blikra, M. A. Pernosky, and R. S. Ødegård, “The thermal state of permafrost in the nordic area during the international polar year 2007–2009,” *Permafrost and Periglacial Processes*, vol. 21, no. 2, pp. 156–181, 2010. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/ppp.687>
- [14] G. Vieira, J. Bockheim, M. Guglielmin, M. Balks, A. A. Abramov, J. Boelhouwers, N. Cannone, L. Ganzert, D. A. Gilichinsky, S. Goryachkin, J. López-Martínez, I. Meiklejohn, R. Raffi, M. Ramos, C. Schaefer, E. Serrano, F. Simas, R. Sletten, and D. Wagner, “Thermal state of permafrost and active-layer monitoring in the antarctic: Advances during the international polar year 2007–2009,” *Permafrost and Periglacial Processes*, vol. 21, no. 2, pp. 182–197, 2010. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/ppp.685>
- [15] S. Smith, V. Romanovsky, A. Lewkowicz, C. Burn, M. Allard, G. Clow, K. Yoshikawa, and J. Throop, “Thermal state of permafrost in north america: a contribution to the international polar year,” *Permafrost and Periglacial Processes*, vol. 21, no. 2, pp. 117–135, 2010. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1002/ppp.690>
- [16] M. Legendre, J. Bartoli, L. Shmakova, S. Jeudy, K. Labadie, A. Adrait, M. Lescot, O. Poirot, L. Bertaux, C. Bruley, Y. Coute, E. Rivkina, C. Abergel, and J.-M. Claverie, “Thirty-thousand-year-old distant relative of giant icosahedral dna viruses with a pandoravirus morphology,” *Proceedings of the National Academy of Sciences of the United States of America*, vol. 111, 03 2014.
- [17] J. A. Screen and I. Simmonds, “The central role of diminishing sea ice in recent arctic temperature amplification,” *Nature*, vol. 464, no. 7293, pp. 1334–1337, 2010. [Online]. Available: <https://doi.org/10.1038/nature09051>
- [18] M. Serreze, A. Barrett, J. Stroeve, D. Kindig, and M. Holland, “The emergence of surface-based arctic amplification,” *The Cryosphere*, vol. 3, 02 2009.
- [19] W. J. S. et al, “A 2018 horizon scan of emerging issues for global conservation and biological diversity,” *Trends in Ecology and Evolution*, vol. 33, no. 1, pp. 47–58, 2018. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0169534717302896>
- [20] J. Fox-Skelly, “There are diseases hidden in ice, and they are waking up,” *BBC Earth*, 2017.
- [21] Centers for Disease Control and Prevention, “What is anthrax?” 2020. [Online]. Available: <https://www.cdc.gov/anthrax/basics/index.html>
- [22] B. Revich, N. Tokarevich, and A. J. Parkinson, “Climate change and zoonotic infections in the russian arctic,” *International Journal of Circumpolar Health*, vol. 71, p. 18792, 7 2012. [Online]. Available: <https://pubmed.ncbi.nlm.nih.gov/22868189>
- [23] V. E. Repin, V. G. Pugachev, O. S. Taranov, and E. V. Brenner, “Potential hazard of microorganisms which came from the past,” *Yukagir mammoth. Saint-Petersburg*, vol. 90, p. 183, 2007.
- [24] J. Taubenberger, J. Hultin, and D. Morens, “Discovery and characterization of the 1918 pandemic influenza virus in historical context.” *Antiviral therapy*, vol. 12 4 Pt B, pp. 581–91, 2007.
- [25] P. Biagini, C. Thèves, P. Balaesque, A. Gérard, C. Cannet, C. Keyser, D. Nikolaeva, P. Gérard, S. Duchesne, L. Orlando, E. Willerslev, A. Alekseev, P. Micco,

- B. Ludes, and E. Crubezy, “Variola virus in a 300-year-old siberian mummy,” *The New England journal of medicine*, vol. 367, pp. 2057–9, 11 2012.
- [26] S. Duchene and E. Holmes, “Estimating evolutionary rates in giant viruses using ancient genomes,” *Virus Evolution*, vol. 4, 02 2018.
- [27] T. F. F. Ng, L.-F. Chen, Y. Zhou, B. Shapiro, M. Stiller, P. Heintzman, A. Varsani, N. Kondov, W. Wong, X. Deng, T. Andrews, B. Moorman, T. Meulendyk, G. MacKay, R. Gilbertson, and E. Delwart, “Preservation of viral genomes in 700-y-old caribou feces from a subarctic ice patch,” *Proceedings of the National Academy of Sciences of the United States of America*, vol. 111, pp. 16 842–16 847, 10 2014.
- [28] J. Steffan, J. Derby, and E. Brevik, “Soil pathogens that may potentially cause pandemics, including sars coronaviruses,” *Current Opinion in Environmental Science and Health*, vol. 17, pp. 35–40, 09 2020.
- [29] D. Johnson, F. Martin, J. Cairney, and I. Anderson, “The importance of individuals: Intraspecific diversity of mycorrhizal plants and fungi in ecosystems,” *The New phytologist*, vol. 194, pp. 614–28, 05 2012.
- [30] S. Gianinazzi, A. Gollotte, M.-N. Binet, D. van Tuinen, D. Redecker, and D. Wipf, “Agroecology: the key role of arbuscular mycorrhizas in ecosystem services,” *Mycorrhiza*, vol. 20, no. 8, pp. 519–530, 2010. [Online]. Available: <https://doi.org/10.1007/s00572-010-0333-3>
- [31] G. Rambold, “The diversity of lichenised fungi: Ecosystem functions and ecosystem services,” *Recent Advances in Lichenology: Modern Methods and Approaches in Lichen Systematics and Culture Techniques*, vol. 2, pp. 121–146, 2015.
- [32] M. Bultman, F. Fisher, and D. Pappagianis, *The Ecology of Soil-Borne Human Pathogens*, 01 2013, pp. 477–504.
- [33] E. C. Brevik, L. Slaughter, B. R. Singh, J. J. Steffan, D. Collier, P. Barnhart, and P. Pereira, “Soil and human health: Current status and future needs,” *Air, Soil and Water Research*, vol. 13, p. 1178622120934441, 2020. [Online]. Available: <https://doi.org/10.1177/1178622120934441>
- [34] D. J. Baumgardner, “Soil-related bacterial and fungal infections,” *The Journal of the American Board of Family Medicine*, vol. 25, no. 5, pp. 734–744, 2012. [Online]. Available: <https://www.jabfm.org/content/25/5/734>
- [35] M. McMullan, M. Rafiqi, G. Kaithakottil, B. J. Clavijo, L. Bilham, E. Orton, L. Percival-Alwyn, B. J. Ward, A. Edwards, D. G. O. Saunders, G. Garcia Accinelli, J. Wright, W. Verweij, G. Koutsovoulos, K. Yoshida, T. Hosoya, L. Williamson, P. Jennings, R. Ioos, C. Husson, A. M. Hietala, A. Vivian-Smith, H. Solheim, D. MaClean, C. Fosker, N. Hall, J. K. M. Brown, D. Swarbreck, M. Blaxter, J. A. Downie, and M. D. Clark, “The ash dieback invasion of europe was founded by two genetically divergent individuals,” *Nature Ecology & Evolution*, vol. 2, no. 6, pp. 1000–1008, 2018. [Online]. Available: <https://doi.org/10.1038/s41559-018-0548-9>
- [36] R. Mitchell, J. Beaton, P. Bellamy, A. Broome, J. Chetcuti, S. Eaton, C. Ellis, A. Gimona, R. Harmer, A. Hester, R. Hewison, N. Hodgetts, G. Iason, G. Kerr, N. Littlewood, S. Newey, J. Potts, G. Pozsgai, D. Ray, D. Sim, J. Stockan, A. Taylor, and S. Woodward, “Ash dieback in the uk: A review of the ecological and conservation implications and potential management options,” *Biological Conservation*, vol. 175, pp. 95–109, 2014. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0006320714001700>
- [37] A. C. et al., “Quantifying drivers of antibiotic resistance in humans: a systematic review,” *The Lancet Infectious Diseases*, vol. 18, no. 12, pp. 368–378, 2018.
- [38] M. Frieri, K. Kumar, and A. Boutin, “Antibiotic resistance,” *Journal of Infection and Public Health*, vol. 10, no. 4, pp. 369–378, 2017. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1876034116301277>
- [39] A. C. Pawlowski, W. Wang, K. Koteva, H. A. Barton, A. G. McArthur, and G. D. Wright, “A diverse intrinsic antibiotic resistome from a cave bacterium,” *Nature Communications*,

- vol. 7, no. 1, p. 13803, 2016. [Online]. Available: <https://doi.org/10.1038/ncomms13803>
- [40] C. C. Blackburn and A. Natsios, "The growing threat of pandemics: Enhancing domestic and international biosecurity," 2017.
- [41] O. Outhwaite, "The international legal framework for biosecurity and the challenges ahead," *Review of European Community & International Environmental Law*, vol. 19, no. 2, pp. 207–226, 2010. [Online]. Available: <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1467-9388.2010.00678.x>
- [42] R. M. Atlas and J. Reppy, "Globalizing biosecurity," *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, vol. 3, no. 1, pp. 51–60, 2005, PMID: 15853455. [Online]. Available: <https://doi.org/10.1089/bsp.2005.3.51>
- [43] M. Oliveira, G. Mason-Buck, D. Ballard, W. Branicki, and A. Amorim, "Biowarfare, bioterrorism and biocrime: A historical overview on microbial harmful applications," *Forensic Science International*, vol. 314, p. 110366, 2020. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0379073820302280>
- [44] Centers for Disease Control and Prevention - National Center for Emerging and Zoonotic Infectious Diseases (NCEZID), "The threat of an anthrax attack," 2020. [Online]. Available: <https://www.cdc.gov/anthrax/bioterrorism/threat.html>
- [45] L. Koch, A.-A. Lopes, A. Maiguy, S. Guillier, L. Guillier, J.-N. Tournier, and F. Biot, "Natural outbreaks and bioterrorism: How to deal with the two sides of the same coin?" *Journal of Global Health*, vol. 10, 08 2020.
- [46] V. Radosavijevic, *Environmental Health and Bioterrorism*, 12 2011, pp. 392–399.
- [47] A. Rossodivita, A. Visconti, T. Saporito, and G. Rizzardini, "Bioterrorism: toxins as potential biological weapons - an emerging global health threat," *International Journal of Infectious Diseases*, vol. 79, p. 55, 02 2019.
- [48] T. Chugh, "Bioterrorism: Clinical and public health aspects of anthrax," *Current Medicine Research and Practice*, vol. 9, 05 2019.
- [49] V. Timofeev, I. Bahtejeva, R. Mironova, G. Titareva, I. Lev, D. Christiany, A. Borzilov, A. Bogun, and G. Vergnaud, "Insights from bacillus anthracis strains isolated from permafrost in the tundra zone of russia," *PLOS ONE*, vol. 14, no. 5, pp. 1–21, 05 2019. [Online]. Available: <https://doi.org/10.1371/journal.pone.0209140>
- [50] M. Pal, Tsegaye, Girzaw, W. Hailegebrael, V. Godishala, and R. K v, "An overview on biological weapons and bioterrorism," *American Journal of Biomedical Research*, vol. 5, pp. 24–34, 04 2017.

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Conflict of interest The Author declares no conflict of interest.