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Impact of climate change on infectious diseases and antimicrobial resistance – Part 1 of the German Status Report on Climate Change and Health 2023

Contents

Impact of climate change on infectious diseases and antimicrobial resistance – Part 1 of the German Status Report on Climate Change and Health 2023

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Together we can counter the effects of climate change

Climate change is the greatest challenge facing humanity, threatening our livelihoods and our secure future. The impact of anthropogenic environmental change on human health and well-being is increasing. Public health systems worldwide need to address this significant and complex burden by strengthening both their capacity to act and their resilience.

As highlighted in the Roadmap of the International Association of National Public Health Institutes (IANPHI) and supported by the G7 health ministers in a communiqué, national public health institutes have a key role to play in climate change mitigation and adaptation [1, 2]. Nutrition and mobility are particularly relevant in this context, as health-promoting behaviour in these fields simultaneously aids climate protection, as does the transformation to sustainable and resilient (public) health systems. Within the framework of the German Strategy for Adaptation to Climate Change (DAS), health is an important topic when considering effective and sustainable measures for dealing with the climate crisis. Climate change affects many other fields that intersect with health, such as water management, construction or urban and regional development. Therefore, health-sensitive climate protection and climate adaptation require intersectoral cooperation and the continuous exchange between different actors in line with the ideas behind One Health and Health in All Policies [3, 4].

In this context, the German Status Report on Climate Change and Health is an important project that can help to address the health challenges of the climate crisis and to strengthen the cooperation between different institutions and authorities. We, the leaders of public authorities in Germany working on public health issues, consider interdisciplinary and intersectoral cooperation to be a key prerequisite for best addressing the health challenges of climate change. This implies the need for innovative and cooperative collaboration between different sectors, not only at the municipal, state and federal level, but also in terms of exchange between these levels.

The German Status Report on Climate Change and Health 2023 is published in an article series in the Journal of Health Monitoring in three issues.

The first issue begins with an introductory article outlining the range of topics covered in the status report, and devotes four thematic articles to the influence of climate change on infectious diseases (vector- and rodent-borne diseases, waterborne infections and intoxications, foodborne infections and intoxications) and antimicrobial resistance.

In the second issue, six articles describe the influence of climate change on non-communicable diseases caused by heat and other extreme weather events such as floods, by increased UV radiation, by allergic diseases and by increased air pollution. The impact of climate change on mental health is also discussed.

The findings from these first two issues are incorporated into the contributions of the final issue. They examine health equity with regard to the effects of climate change, highlight the importance of target group-specific climate change communication, and make concluding recommendations for action based on those formulated in the other articles.

In addition to the various topic-specific recommendations, all contributions have one thing in common: they point to a continuing need for research. Extended monitoring of many of the health effects of climate change is also recommended. The cooperation of the authorities and research institutions dedicated to these important tasks is crucial.

We hope that this report will be an important step towards even better cooperation between science and decision-makers in politics and society.

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References
1. International Association of National Public Health Institutes (2021) IANPHI roadmap for action on health and climate change: Engaging and supporting national public health institutes as key climate actors. https://ianphi.org/news/2021/roadmap-climate-change.html (As at 30.03.2023)
2. G7 (2022) Communiqué of the G7 Health Ministers, 20 May 2022, Berlin. https://www.bundesgesundheitsministerium.de/fileadmin/Dateien/3_Downloads/G/G7/20220520_German_G7_Health_Ministers_Communique.pdf (As at 30.03.2023)
3. One Health High-Level Expert Panel (2022) One Health: A new definition for a sustainable and healthy future. PLoS Pathog 18(6):e1010537
4. World Health Organization (2023) Promoting Health in All Policies and intersectoral action capacities. https://www.who.int/activities/promoting-health-in-all-policies-and-intersectoral-action-capacities (As at 30.03.2023)

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Climate change and public health in Germany – An introduction to the German status report on climate change and health 2023

Abstract

Global warming of 1.5°C and even 2°C is likely to be exceeded during the 21st century. Climate change poses a worldwide threat and has direct and indirect effects on infectious diseases, on non-communicable diseases and on mental health. Not all people are equally able to protect themselves against the impacts of climate change; particularly populations that are vulnerable due to individual factors (children, older persons, those immunocompromised or with pre-existing conditions), social factors (the socially disadvantaged), or living and working conditions (e.g. people who work outdoors) are subject to an increased risk. Concepts such as One Health or Planetary Health provide a framework to frame both climate change itself and adaptation strategies or sets of actions for environmental human and animal health. Knowledge of climate change impacts has grown in recent years, and mitigation and adaptation strategies have been developed.

This is part of a series of articles that constitute the German Status Report on Climate Change and Health 2023 and provides background to the technical articles that follow in this and two other Special Issues of the Journal of Health Monitoring.

PUBLIC HEALTH · CLIMATE CHANGE · ADAPTATION · RESILIENCE · HEALTH

1. Preamble to the Status Report on Climate Change and Health 2023

Climate change poses one of the greatest threats to many people worldwide and has direct and indirect effects on communicable and non-communicable diseases. In view of the major health challenges, the German Federal Ministry of Health (BMG) is funding the project 'Climate Change and Health – Status Report/Update with Advisory Board: Content, Communication, Working Methods' (KlimGesundAkt), which is coordinated at the Robert Koch Institute (RKI, Germany's national public health institute) and aims to update the 2010 Status Report on Climate Change and Health with a focus on Germany [1]. This update differs from the previous report in two ways:

(1) in the presence of an interdisciplinary and cross-institutional advisory board, which accompanies the entire planning and publication process of the updated status report,

(2) in the downstream target group-oriented communication and condensation of the results in the form of intuitive communication tools, including the formulation of recommendations for action.

Table 1
Overview of all articles in three Special Issues in the Journal of Health Monitoring's Climate Change and Health series

Issue	Topic
Introduction to the topic of climate change and health	
1	Introduction to the Status Report on Climate Change and Health
Impact of climate change on infectious disease…	
1	…by vector- and rodent-associated diseases.
1	…due to waterborne infections and intoxications
1	…due to foodborne infections and intoxications
1	…through antimicrobial resistance
Impact of climate change on non-communicable disease…	
2	…due to temperature changes
2	…due to extreme weather events
2	…due to UV radiation
2	…due to allergen exposure
2	…due to air pollutants
Impact of climate change on mental health.	
2	Impact of climate change on mental health.
Cross-cutting issues related to climate change and health	
3	Social determinants of the health impacts of climate change
3	Target group-specific communication
3	Options for action and implications

The steps of this participatory and transparent process, which involved government authorities, university institutions and civil society, are outlined here.

The task of the interdisciplinary and cross-institutional advisory board was to deliberate on the report's structure, scope and thematic focus. As a result, less space has been devoted to the causes of climate change than in the 2010 report, whereas other areas such as mental health and social inequality have been expanded or newly included. The coordination process took place in close cooperation with the internal RKI working group 'Climate Change and Health', which is independent of the project. This group brings together the RKI's knowledge of topics such as waterborne infections, heat-related mortality, vector-associated diseases, climate-related health behaviour, mental health surveillance and allergies, which is spread across various organisational units.

The status report will be published as a collection of articles in the Journal of Health Monitoring's Climate Change and Health series in three journal issues (Table 1).

Global man-made climate change will continue to progress and affect human health.

This reflects contemporary scientific publication practices and provides greater availability of the results to the public health community. Primary addressees are the interested professional public as well as decision-makers with a remit in public health. Since the Journal of Health Monitoring is published in German and English, and the English edition is archived at PubMed Central and accessible via PubMed search, international visibility is also ensured.

Authors with the desired expertise were identified on the basis of the topics to be addressed. A dual role for members of the advisory board as authors was encouraged. Additional scientists were consulted by the authors of the individual chapters where their expertise was needed. This process resulted in a group of more than 90 authors from over 30 research institutions and government agencies who are responsible for updating the Status Report on Climate Change and Health 2023.

Another important component of this project is targeted downstream science communication, which processes the results and recommendations contained in the individual articles through a wide range of tools (videos, fact sheets, social media content, digital channels, direct exchange formats) for specific target groups with public health relevance. This evidence-based communication strategy was developed at the RKI in close coordination with the advisory board and the Federal Centre for Health Education (BZgA). Some communication tools are to be tested and further developed in a participatory and iterative process involving target groups such as decision-makers and relevant stakeholders at the subnational level. Health communication is an important public health intervention in the field of climate change and health. Relevant decision-makers and the public need to know and assess increasing risks in order to act based on them.

2. Health, climate and climate change adaptation in Germany

The article presented here provides a general overview of climate change and health as the basis for the status report, particularly the climatic background and climate change-related health risks. Other articles that follow in this and two other Special Issues of the Journal of Health Monitoring (Table 1) summarise the current evidence in the various fields, briefly touched on here, in which climate change interacts with wildlife and the environment to affect human health.

In the long term, the health situation in Germany has been improving steadily. For example, since the early 1990s, life expectancy of people in Germany has increased by around four years to 83.4 years for women and by around six years to 78.5 years for men [2, 3]. Notwithstanding the increase in life expectancy, the effects of global climate change are increasingly becoming an important risk factor for health. Especially in the last few years, it has become apparent how fast climate change is reaching us. 2022 was the warmest year on record in Germany, and a pronounced spring drought occurred for the fourth year in a row [4]. Climate change will also make certain disasters more frequent, such as the heavy rain event that led to widespread flooding in July 2021, especially in Rhineland-Palatinate and North Rhine-Westphalia. Extreme events such as these can trigger disasters that are not the result of a single event, but must be understood as an interplay of different processes, modified by local conditions. These disasters may have an immediate impact, such as a physical effect on human health. However, cascading effects can also result in broader and far-reaching indirect health consequences, e.g. through lack of accessibility for emergency vehicles or through the development of chronic conditions or mental illness [5]. While climate change is most noticeable in Germany through a change in thermal stress, extreme weather events such as droughts, low water, heavy rain, storms, fires, and floods occur and can also have a strong impact on human health. In addition, there are indirect health effects moderated by natural systems, e.g. a pollen season prolonged by warmth with associated allergy burden, increased exposure to pollutants, and infections due to reduced hygiene after floods [6]. Infectious diseases not currently occurring in Germany to a significant extent are also expected to increase.

Climate change affects human health in part by altering ecosystems and, as one factor among many, exacerbates ongoing biodiversity loss. At the same time, ecosystems and their biodiversity play a role in the fluctuation of greenhouse gases and are an important lever of climate change adaptation [7]. The two crises must therefore be considered together in terms of their consequences for human health (Info box 1). There is a continuing need for research into the links between climate change, biodiversity and health.

Biodiversity contributes directly and indirectly to human health.

So far, the Essential Public Health Functions (EPHFs) of the World Health Organization (WHO) [8] do not yet adequately reflect environmental changes or their role in climate change mitigation and adaptation. This article therefore draws on existing concepts of core public health functions [9] that link these functions to sustainability aspects and climate resilience. Concepts such as One Health and Planetary Health, as well as the public health core functions, are considered in relation to their utility for public health practice to enable health equity in climate change.

Even though climate change has a global dimension and ultimately, effective climate protection can only succeed globally, adaptation measures must be developed and implemented primarily at the regional or local level. Climate protection (mitigation) to prevent the progression of climate change is essential, but climate change adaptation is also important to enable people to remain healthy despite the changes. This status report focuses primarily on climate change adaptation in Germany.

3. Climatic changes

3.1 Climate development

When analysing long-term climate development in Germany, it becomes clear that climate change is already observable and perceptible. It is clearly due to the anthropogenic increase of greenhouse gases in the atmosphere (Info box 2). The most important anthropogenic greenhouse gas in this context is carbon dioxide (CO_2), which caused a change in global radiative forcing of 2.16 W/m² in the period from 1750 to 2019 (Info box 3). Together with other greenhouse gases, such as methane, nitrous oxide, and ozone, this results in total additional positive radiative forcing of 2.72 W/m², which is associated with a global temperature increase of 1.2°C since the start of the 20th century [25]. Since area-wide measurements began in 1881, the annual mean temperature in Germany has increased by 1.6°C degrees. The rate of temperature increase in Germany (as worldwide) has increased significantly over the past 50 years:

Info box 1
Importance of biodiversity for human health

Biodiversity provides ecosystem services, direct and indirect contributions of ecosystems to human well-being, which are essential for human health. The dramatic loss of biodiversity thus poses a threat to human health.

A large number of scientific publications have identified correlations between biodiversity and human health. Research into causal relationships has been funded in Germany since August 2022 with a directive from the Federal Ministry of Education and Research [10].

The diversity of the plant spectrum provides us with medicine and food, regulates water and climate, and reduces environmental risks such as air pollution. In addition, there is a connection of biodiversity with allergies and immune diseases. For example, contact with a microbe-rich environment in childhood, such as through agriculture, has been identified as a protective factor against allergies [11, 12].

Biodiversity also plays a role in infectious diseases. For example, the risk of pandemics may increase due to human destruction and alteration of ecosystems [13]. Unsustainable consumption, agricultural intensification, and wildlife trade lead to increased contact between humans and wildlife, triggering a variety of zoonotic diseases. Thus, biodiversity conservation has an important preventive role.

Contribution of biodiversity to mental health and human well-being

Spending time in nature has a positive effect on human well-being and mental health; this has been well researched for some time. Urban green spaces, gardens, forests, and bodies of water provide opportunities for recreation [14], stress reduction [15], and social interactions.

However, it has not yet been clearly established whether this effect is also stronger the more diverse the nature surrounding humans is, since socioeconomic factors, cultural background and aesthetic preference of the study participants, but also the definition of biodiversity and health of the respective study play a role [16–18].

Cultural ecosystem services also make an important contribution to mental health [19]. People value diverse ecosystems and some species for their beauty, feel connected to them, and identify with a particular environment.

Synergies between climate change adaptation, public health strategies, and conservation

Given the complex interrelationships between climate change, biodiversity loss, and human health (Figure 1), there are important synergies between climate change adaptation, public health measures, and nature conservation [20]. Nature-based solutions can achieve positive outcomes in terms of both health and adaptation to climate change, so-called co-benefits [21]. One example is the expansion of urban green space and urban blue infrastructure. This includes roadside trees and street greenery, greening of facades and green roofs, and larger green spaces (parks, playgrounds) that promote recreation, air pollution control, and microclimate [22]. To simultaneously serve biodiversity conservation, this greenery should be as diverse as possible. Socioeconomically disadvantaged people in particular benefit from nature-based health interventions in cities [23]. In view of increasing urbanisation worldwide – it is predicted that 68% of the world's population will already live in cities by 2050 [24] – the development of urban, diverse greenery should therefore not be underestimated as an important public health measure.

Protecting and restoring biodiversity is an important public health measure.

since 1881, temperatures increased by an average of 0.12°C per decade; for the last 50 years, the warming rate has been more than three times as high, at 0.38°C per decade. Since the 1960s, each decade has been significantly warmer than the previous one. The rise in mean air temperatures is also likely to lead to more and more intense weather extremes in the coming years. The increase in heatwaves and dry spells has a strong impact on health [26].

According to the German coordination office of the Intergovernmental Panel on Climate Change (IPCC), global air temperatures will continue to rise until at least mid-century under all emissions scenarios considered. Global warming of 1.5°C and even 2°C is likely to be exceeded during the 21st century unless drastic reductions in CO_2 and other greenhouse gas emissions occur in the coming years [27]. Many changes in the climate system are amplified in direct relation to increasing global warming [25]. Natural factors and internal variability will modulate human-induced forcing, especially at regional scales and in the near future. It is important to consider these modulations when planning for the full range of potential impacts. As global warming continues, projections indicate that simultaneous and multiple modifications of climatic impact drivers (CIDs) will increasingly occur in nearly all regions. Regional climatic impacts are predominantly negative in nature, although there are some regions that could benefit from climate change. Changes in several CIDs would be more widespread at 2°C compared to 1.5°C global warming, and even more widespread and/or pronounced at higher levels of warming. Effects with low probability of occurrence – such as ice sheet collapse, abrupt changes in ocean circulation, some compound extreme events, and warming substantially beyond the range assessed as very likely – cannot be ruled out and are part of the risk assessment [25].

From a natural science perspective, limiting human-induced global warming to a certain level requires limiting cumulative CO_2 emissions, achieving at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Strong, rapid, and sustained reductions in greenhouse gas emissions would also limit the warming effect resulting from declining air pollution, since aerosols (especially particulate matter) have predominantly negative radiative forcing and their projected decline by mid-century will have an additional warming effect [28].

Info box 2
Greenhouse effect

The greenhouse effect is a natural process that significantly determines the temperature on Earth. Water vapour and carbon dioxide are the two main natural greenhouse gases that cause the global mean temperature to be a comfortable 15°C, rather than -19°C, as it would be without the presence of the Earth's atmosphere. Increasing the concentrations of atmospheric trace gases such as carbon dioxide, methane, and nitrous oxide creates an additional (anthropogenic) greenhouse effect. This results in further warming of the lower atmosphere and affects the entire climate system.

Info box 3
Radiative forcing

The additional radiative forcing is the change in net insolation (incoming solar radiation minus outgoing radiation, expressed in watts per square meter, W/m^2) at the top of the troposphere, the lowest layer of the Earth's atmosphere. This change occurs due to anthropogenic climate change, primarily by increasing the concentration of greenhouse gases in the atmosphere. The additional radiative forcing is defined as the change from the year 1750. The numbers in the representative concentration pathways (RCP) climate scenario names, e.g. RCP2.6 or RCP8.5, refer to the expected change in radiative forcing of 2.6 W/m^2 and 8.5 W/m^2, respectively..

3.2 Climate models and climate projections

Climate models provide information about the future development of the climate. The calculated future projections depend, among other factors, on the assumed development

The direct and indirect effects of climate change on human health are highly dependent on region, social factors, and human behaviour.

of human society. In order to be able to represent these potential global developments, scenarios have been developed over the past decades from which different development paths of emission and concentration scenarios of greenhouse gases and aerosols can be derived. The oldest scenario family (special report on emissions scenarios, SRES) reflects the state of knowledge at the turn of the millennium, the subsequent generation of scenarios (representative concentration pathways, RCP) was developed for the IPCC's Fifth Assessment Report, and now considers other factors such as climate change mitigation and adaptation [29]. The latest generation is called shared socioeconomic pathways (SSP) and focuses on changing socioeconomic factors, such as population, economic growth, education, urbanisation, and the pace of technological development [30]. In doing so, the SSP identify five different ways in which the world could develop without climate policies and how different levels of climate action could be achieved. In doing so, the climate mitigation targets of the RCP are combined with the SSP. The RCP set pathways for greenhouse gas concentrations and thus the amount of warming that could occur by the end of the century. The SSP, on the other hand, provide the framework within which emissions reductions are achieved (or not achieved) [31].

The five socioeconomic development paths of the SSP scenarios (SSP1 to SSP5), are associated with additional radiative forcing (1.9 to 8.5 W/m^2). Scenarios with low or very low greenhouse gas emissions (SSP1-1.9 and SSP1-2.6) lead to detectable positive impacts on greenhouse gas concentrations as well as air quality in a matter of years compared to scenarios with high and very high greenhouse gas emissions (SSP3-7.0 or SSP5-8.5). When comparing these contrasting scenarios, discernible differences between global air temperature trends begin to emerge from natural variability within about 20 years.

4. Impact of climate change on health

The Climate Impact and Risk Assessment 2021 for Germany lists eight climate risks in the field of human health, which are also in line with the structure of this status report and the following sections [32]: heat stress, UV-related health damage, allergic reactions, potentially harmful micro-organisms and algae, distribution and change in abundance of possible vectors, respiratory issues due to air pollution, injuries and deaths as a result of extreme events, and effects on the healthcare system.

These impacts of climate change on humans and the environment are highly dependent on geographic region, human use of the environment, and social determinants [33]. Any person can be affected by diseases that are influenced by, at different temporal scales, weather and climate; nevertheless, there are parts of the population that are much more vulnerable to the health consequences (like heatwaves) of climate change and, in some cases, respond more strongly. In particular, these are individuals vulnerable due to their age or those weakened by immune or other pre-existing conditions. In addition, there are groups of people who are exposed to health-threatening situations longer and more frequently than others due to occupational or private activities [33]. Interdependencies between age, gender, work/housing conditions and location, income or poverty as well as education status also play a role here [34]. In a coming article of this status report on climate change and health, this topic is discussed in more detail (Bolte et al. [35]).

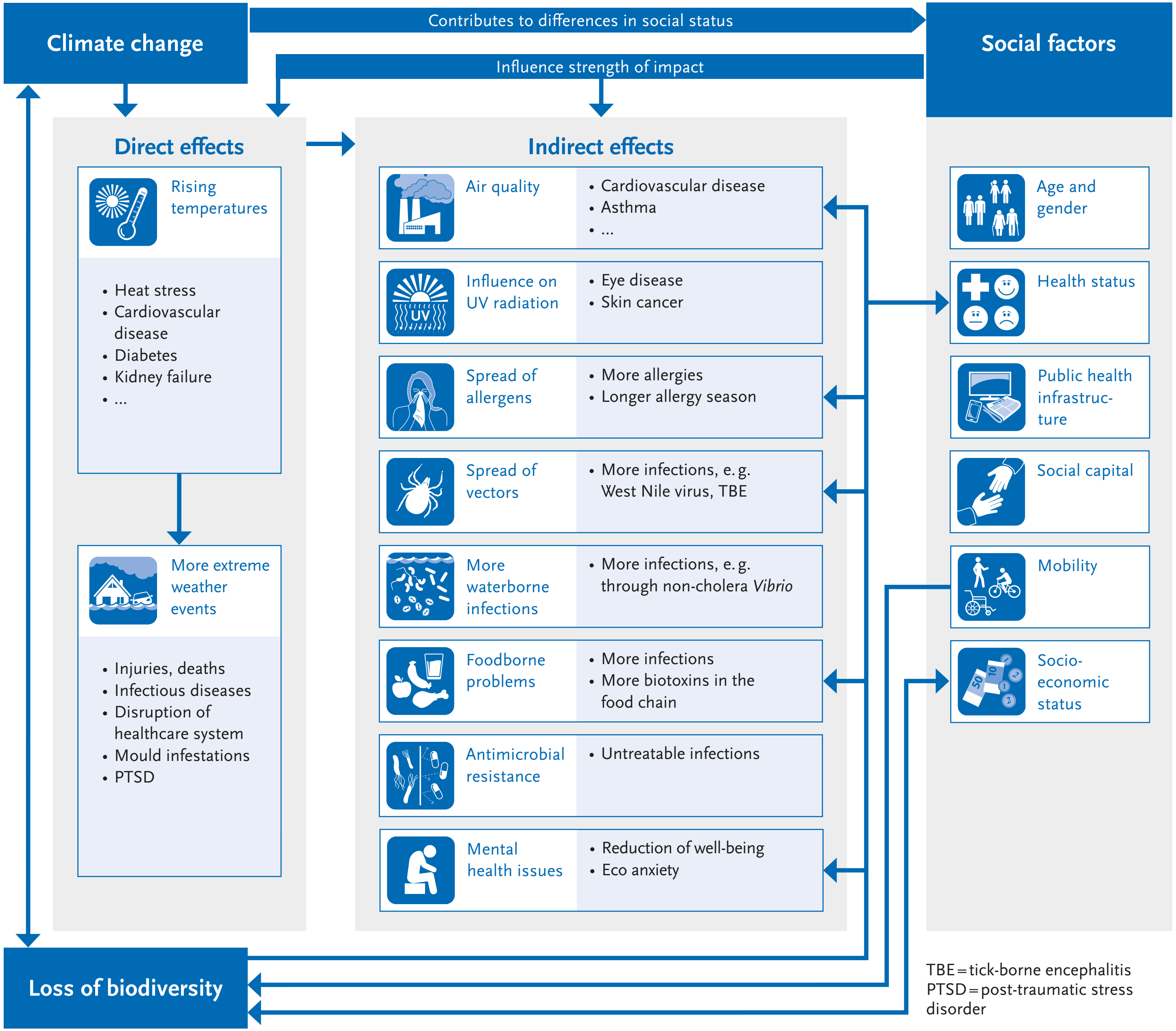
Accordingly, different groups have very different needs and requirements of the healthcare system. This shows that the climate impacts described above not only affect individuals, but also have a significant impact on the healthcare system and its players, and thus have organisational and economic components. Health in particular has many cross-connections with other fields of action [36].

Health is not only an individual concern, but above all a social task. Various prevention and health promotion measures can enable people to behave in a way that promotes health by adapting to climate change and its effects. These include interventions such as educational campaigns, like the website 'Klima-Mensch-Gesundheit' (Climate-Human-Health) of the BZgA. However, these measures should always be combined with a change in people's living conditions, because health behaviour is difficult to enforce against resistance from the social environment or living conditions. These so-called structural preventive measures include, for example, the expansion of infrastructure and services offered (e.g. bicycle paths, climate-friendly cafeteria food, shaded public areas, access to urban greenery) or pricing policies (e.g. promoting climate-neutral construction). These complex interventions require the involvement of many social groups and sectors beyond health, for example by cooperating with actors from the transport, construction or environmental sectors. Such an approach requires that health is considered in all policies, so that health-promoting lifestyles actually become the easiest for people in everyday life, as the WHO demands ('Make the healthy way the easy way') [37].

Many consequences of global warming interact with each other and can reinforce each other through feedback effects. In addition to the direct effects of climate change on human health – in Western Europe primarily through increased occurrence of extreme weather events such as heatwaves – indirect effects can also be observed, which are brought about through changes in natural systems (atmosphere, bio-, hydro-, cryo- and pedosphere) (Figure 1). Weather conditions determine the local meteorological conditions to a large extent, as well as air and radiation hygiene. For example, long-lasting summer high-pressure weather conditions not only lead to thermal stress due to high air temperatures, but also to increased exposure to ozone and UV radiation. Climate change causes changes to infectious diseases whose pathogens are transmitted via blood-sucking arthropods, infections that are water or food-related, and changes in the area of allergenic plants and animals. In addition, progressive climate change can cause further changes relevant to health, like an increase in drought episodes, which indirectly affect health, e.g. via insufficient water supply, crop failures or the increase in forest fires, or an increase in flooding events, which can lead to the spread of certain pathogens. Both are already a major challenge today [38–40].

The various impacts of climate change on health are briefly touched on here and addressed in detail in subsequent articles in this and the next Special Issue in the Climate Change and Health series of articles, with reference to both communicable diseases and non-communicable diseases, including mental health impairments.

Figure 1
Direct and indirect effects of climate change on health
Illustration: Robert Koch Institute



TBE = tick-borne encephalitis
PTSD = post-traumatic stress disorder

Climate change has an impact on people's physical and mental health. Not all people can protect themselves equally well against climate change impacts.

4.1 Impact of climate change on communicable diseases

Vector and rodent associated infectious diseases

According to a study by McIntyre et al. [41], nearly two-thirds of the human and domestic animal disease pathogens found in Europe are climate sensitive. Climatic conditions favour, among other things, the outbreak of vector-associated diseases such as chikungunya, dengue, and West Nile fever in Europe and contribute to the further geographic spread of vectors that transmit the causative agents of Lyme borreliosis and tick-borne encephalitis.

Transmission of vector-associated pathogens requires an introduced or established vector population, a pathogen, and appropriate environmental and climatic conditions throughout the pathogen transmission cycle. Environmental and climatic conditions affect each of these areas, from vector survival and abundance to pathogen growth and survival in vector organisms, to vector activity and sting frequencies, to human exposure to disease vectors.

Even if, for example, the introduction of *Aedes albopictus* (Asian tiger mosquito) is primarily favoured by globalisation, especially along transport routes [42], climate change is associated with the active potential spread of vectors and pathogens, which is why a further shift of certain tick species to higher latitudes and altitudes and a further geographical spread of mosquito and sandfly species should be expected in Germany in the coming years [43]. Another article in this status report is dedicated in detail to vector- and rodent-associated diseases in climate change (Beermann et al. [44])

Waterborne infections and intoxications

Waterborne pathogens may also be subject to the influence of climate change. The increase in sea surface temperatures, as evidenced by measurements in the North Sea and Baltic Sea (in the North Sea, temperature increased by about 1.3°C over the last 50 years) [45], will continue in the future and accelerates the proliferation of the bacterial genus *Vibrio*, for example [46, 47]. *Vibrio* infections mainly manifest as wound infections and diarrhoeal diseases. Climate warming with accompanying increased water temperatures could lead to higher *Vibrio* concentrations, making an increase in infections more likely [47–49]. Projections indicate that the sea surface temperature of the North Sea will warm by 1°C to 3°C by the end of the 21st century, and that of the Baltic Sea by 3°C to 4°C, with strongest warming rates in the northern part of the Baltic Sea [50]. In addition, extreme precipitation events may lead to outbreaks of waterborne diseases [49]. The topic of waterborne infections and intoxications is dealt with in more detail in another article in this status report (Dupke et al. [51]).

Foodborne infections and intoxications

Foodborne infections and intoxications also play a role in the context of climate change, as the incidence of associated diseases can be affected by temperature changes. Examples include bacterial gastrointestinal infections caused by the mostly foodborne pathogens *Campylobacter* and *Salmonella*. Transmission to humans usually occurs through food. *Salmonella* infections increase linearly with air temperature by 5 to 10% per °C [52]. Thus, longer summers allow increased transmission of foodborne pathogens [49].

More detailed findings can be found in another paper in this status report (Dietrich et al. [53]).

Antimicrobial resistance (AMR)

One link between health and climate change that has received little attention is antibiotic-resistant infections [54]. Bacteria that cause infections in humans can develop resistance to antibiotics. Resistance against antimicrobial agents (in bacteria and other microbes) causes significant morbidity and mortality worldwide, posing enormous challenges to health systems and basic public health functions globally. Antibiotic resistance in bacteria is thought to develop mainly under the selection pressure of antibiotic use. However, other factors, such as climate change, may also contribute to the increase in antibiotic resistance. MacFadden et al. [55] reported that a 10°C increase in temperature in experimental laboratory settings was associated with an increase in antibiotic resistance in the common pathogens *Escherichia coli* (+4.2%), *Klebsiella pneumoniae* (+2.2%), and *Staphylococcus aureus* (+2.7%). In another contribution to this status report, Meinen et al. [56] provide a systematic review on AMR in climate change.

4.2 Impact of climate change on non-communicable diseases and mental health

Health impact due to air pollutants

In recent decades, air quality in Germany has improved considerably thanks to targeted air pollution control measures [57]. However, if emissions remain constant, there would be an increase in ground-level ozone and particulate matter concentrations as a result of climate change. Warmer summers and, in particular, an increase in extreme temperature events favour the formation of ground-level ozone, as stagnant air circulation during pronounced high-pressure weather conditions can cause ozone to accumulate and allow peak levels to occur over several days [58, 59]. Increased particulate matter exposure, e.g. due to increasingly dry soils and more frequent vegetation fires, can cause cardiovascular disease in addition to impaired lung function and serious lung diseases such as asthma and lung cancer. Likewise, there is a significant relationship between cardiovascular mortality and levels of ground-level ozone, with even short-term exposure to ozone increasing health risk and moderately high levels of ozone being associated with increasing rates of myocardial infarction [60, 61]. Further health impacts arise from increased heat stress, especially in combination with increased air pollutants [62, 63]. In a contribution to this status report, Breitner-Busch et al. [64] provide an overview of climate change-related health effects from air pollutants that are particularly relevant for Germany, and explain the effects of air pollutants in conjunction with air temperature. Furthermore, an overview of limit, target and guideline values in the current context of the air situation in Germany is given, and the current WHO guideline values are discussed. Corresponding recommendations for the public health sector are presented.

Health impact due to heat

Heat events usually occur over large areas and affect individual groups, especially younger and older people, but are also cross-sectoral [65]. Heatwaves will increase in terms of intensity, duration, and frequency (Figure 2).

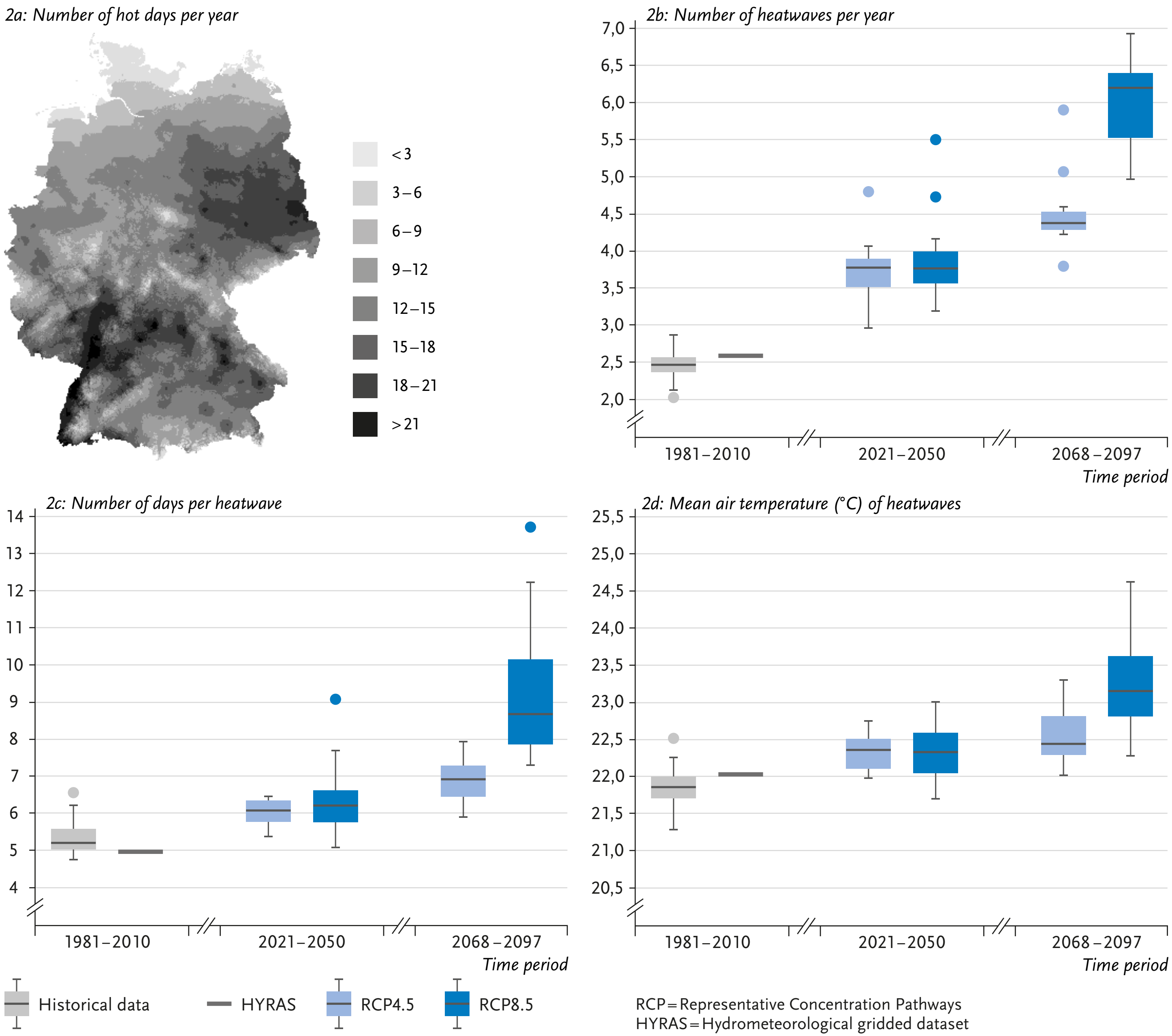
Figure 2a
Number of hot days per year. Regional distribution of the number of hot days with a maximum temperature of at least 30°C, 2011–2020
Source: German Meteorological Service

Figure 2b
Number of heatwaves per year

Figure 2c
Number of days per heatwave

Figure 2d
Mean air temperature (°C) of heatwaves

2b–2d
in Germany, based on historical (measured) datasets, HYRAS (gridded dataset) [69], and projections under the RCP4.5 and RCP8.5 climate scenarios
Source: Own representation based on Schlegel et al. [67]



The characteristics of heatwaves, their number, duration, and intensity, as well as their temporal occurrence within a year, are relevant for estimating the health burden during and after high thermal stress. In particular, the duration of a heatwave can increase mortality, and the disproportionate increase in long heatwaves can therefore lead to a sharp increase in the number of deaths [66]. For example, RCP scenarios for Germany project an increase in mortality from chronic lower respiratory diseases (CLRD) during long heatwaves (≥10 days) of up to 150% by mid-century. Depending on the scenario, there could be an increase of between 260% (RCP4.5) to a maximum of 540% (RCP8.5) by the end of the century. According to RCP4.5 and RCP8.5, mortality from ischemic heart disease (IHD), which involves narrowing of the coronary arteries, could be 90% (RCP4.5) or 150% (RCP8.5) higher between 2021 and 2050, and as much as 330% (RCP4.5) higher to a maximum of 900% (RCP8.5) between 2068 and 2097 [67]. This indicates that even under moderate climate change, significant health effects from heat can be expected. In a subsequent article of this status report Winklmayr et al. [68] address the health effects of high temperatures, which particularly affect older persons and people with certain pre-existing conditions.

Health impacts from extreme weather events

Increases in intense rainfall can cause devastating floods that directly affect the lives and health of the population and health infrastructure. The intensity of rainfall in Germany and Western Europe has already increased by up to 19% due to climate change. Flooding events, such as those in western Germany and Belgium in 2021, have become up to nine times more likely. If global warming approaches the 2°C threshold, this will be directly reflected in precipitation intensities (increase of up to 6%) and flood probabilities [70].

However, increased dryness and drought must also be expected, especially in the summer months. Modelling has shown that with a warming of 3°C by the end of the century, twice as many days of drought are to be expected in Germany [71]. Historical data show that various regions of Germany are already suffering from increasing drought [72]. In addition to stressful situations in agriculture, low water levels and falling groundwater levels, this can also have an impact on air quality. Dry soils contribute to a worsening of air quality by dust and particulate matter due to drifting. Prolonged drought also increases the time pollen stays airborne, and more frequent forest fires contribute locally to increased exposure to particulate matter. Drought stress in plants also reduces the uptake of ozone, thereby increasing the ground-level ozone concentration that is harmful to health, and thus increasing the incidence of respiratory diseases [73]. In another contribution to this status report, Butsch et al. [74] provide an overview of health impacts due to increased extreme weather events occurring under climate change. According to this article, such indirect or long-term meteorological consequences can be countered by risk management and disaster relief in order to mitigate the health consequences of extreme events as far as possible, especially for vulnerable groups.

Health effects due to increased allergen exposure

Climate change has an influence on allergen exposure. For example, increased pollen production and an earlier pollen season support the occurrence and increase the frequency of pollen-associated allergic respiratory diseases [75]. In addition, higher temperatures and an increase in the air's CO_2 content can lead to an increase in the allergenicity of pollen and thus cause stronger allergic reactions [76]. Climate change-induced changes in vegetation zones also allow alien species to colonise and spread in areas where they were not previously native. For Europe, for example, the ragweed plant with its high allergenic potential is a cause for concern [6, 75, 77]. Bergmann et al. [78], in another contribution to this status report, deal in detail with the topic of climate change-induced changes in allergen exposure and their health consequences, show the connection to other exposures such as air temperature and air pollutants, and give recommendations for action.

Health effects due to altered UV radiation exposure

Climate change has an influence on ground-level UV radiation and the annual UV radiation dose. For Germany, the effects of greenhouse gases on stratospheric ozone and especially cloud cover play a decisive role here. Projections for stratospheric ozone and cloud density are subject to very large uncertainties. However, in recent years, a significant increase in sunshine duration has been recorded in Germany and, consequently, an increase in the daily sums of erythemally effective UV radiation annual dose [79, 80]. The occurrence of UV radiation-related diseases of the skin and eyes, including cancers, depends not only on the prevailing ground-level UV irradiance in the environment (ambient UV radiation) of people and the UV radiation annual dose, but is also decisively determined by the exposure behaviour of people. The current state of knowledge on effects of climate change on UV radiation exposure and health consequences are described in a contribution to this status report by Baldermann et al. [81].

Impact of climate change on mental health

In addition to increasing general concern among many people about the future of the planet, climate change may have other consequences for mental health. The effects of climate change-related weather events and natural disasters on mental health have been known for some time. They cause problems such as sleep disorders, stress, anxiety, depression, and the development of post-traumatic stress disorder and suicidal ideation [82]. However, less research has been done on the psychological and emotional consequences generated by awareness of the slow and gradual changes in the environment caused by human-induced climate change and what measures can effectively protect vulnerable groups in particular. Studies show that people experience feelings of loss, helplessness, and frustration due to the threat of climate change – a condition now referred to as eco anxiety [83]. In a further contribution to this status report, Gebhardt et al. [84] address this issue and examine the topics of extreme weather events, temperature increase, perception and inner-psychological processing of climate change, psychological-sociological aspects, as well as the ability to act and resilience factors.

5. Conceptual frameworks for addressing the climate crisis

The concepts of One Health and Planetary Health have gained momentum since the early 2000s; they can provide a framework for addressing the climate crisis. Inherent in their systemic-holistic approach is a broader view of possible solutions to problems of environmental change and health.

Both concepts are subject to constant further development and thus do not represent rigid monoliths. As a result, both approaches can be instrumental in achieving many of the goals of the United Nations' '2030 Agenda for Sustainable Development' (Sustainable Development Goals), thus significantly strengthening that agenda and ultimately improving environmental health [85]. The impacts of climate change affect variously interrelated systems, such as the relationship between the economy, energy, the environment, and health, and thus can only be understood and resolved across these fields [27]. In order to improve the protection of human health, the interrelationships between human and animal health and healthy ecosystems must therefore be considered more seriously in a wide range of policy areas.

5.1 One Health

The concept of One Health was proposed by Schwabe [86] in 1964, when he coined the term 'One Medicine' for the areas encompassing human and veterinary health. Since then, the concept of One Health has been extended to include the environmental aspect: humans are a part of the animal kingdom, which in turn is embedded in a common environment [87]. The 'Berlin Principles' recently further enriched the One Health concept [88]. They emphasise the institutional strengthening needed to ensure the translation of science-based knowledge into policy and practice, as well as the need for action in addressing the climate crisis.

The One Health High-Level Expert Panel (OHHLEP) was convened by WHO and other organisations in order to initiate the implementation of the One Health approach from theory to practice. Four areas were deemed essential: communication, coordination, collaboration, and capacity building [89]. The balance between sectors and disciplines should be considered, sociopolitical and multicultural parity, socioecological balance, human responsibility, as well as transdisciplinarity and multisectoral collaboration across all relevant disciplines.

Through the One Health concept, a holistic view of all affected areas can reinforce synergistic approaches along responsible administrative and executive levels, in order to achieve solutions that can reduce the effects of climate change or implement adaptation strategies. For example, the costs resulting from the emergence of new zoonoses could be significantly lower if they were identified early on as potential zoonoses in animals rather than appearing later in humans [90].

5.2 Planetary Health

Planetary Health is a concept that relates human health to political, economic, and social systems, as well as the ecological boundaries of our planet [91]. It highlights the dominance and impact of human activities on shaping our environment, and calls for the associated responsibility and recognition of planetary boundaries. By transforming toward health within planetary boundaries, ecological stress limits are no longer exceeded, while current and future generations are enabled to live healthy, dignified lives in safety through effective and sustainable political, social, and economic systems [92]. Planetary Health is a health narrative based on sustainability and the critique of growth economies, which builds on interdisciplinary as well as intersectoral engagement with the complex relationships between and within ecosystems. The understanding of Planetary Health goes beyond the isolated consideration of environment and climate. In Germany, political Planetary Health recommendations for the field of climate change and health were formulated in the 2021 Lancet Countdown Policy Brief as follows [93]:

(1) the systematic and widespread implementation of heat-health action plans to reduce heat-related health risks,

(2) the reduction of the CO_2 footprint of the German healthcare sector and

(3) the integration of climate change and health/Planetary Health in education and training of health professionals.

5.3 Climate change mitigation and adaptation as tasks for the health care system

Evidence and knowledge about the impact of climate change have continued to grow in recent years, and climate change mitigation and adaptation strategies have been developed both globally and nationally.

Pivotal at the global level is the Paris Agreement, which was adopted at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (COP21) in December 2015. The signatory states pledged to limit global warming to well below 2°C, but preferably to 1.5°C, compared with pre-industrial levels. At COP26 in Glasgow, all states agreed to accelerate the global energy transition away from coal combustion; at COP27 2022 in Egypt, this acceleration was not evident.

In 2022, the German G7 presidency placed climate change and health on the political agenda of those seven industrialised countries that have joined together as the 'Group of 7', thus promoting national and international attention to climate-neutral and climate-resilient health systems.

At the federal level, the Climate Change Act guides the actions of the healthcare system in enforcing climate protection. This law was amended by a decision of the Federal Constitutional Court. The decision stated that requiring only a mild reduction in CO_2 consumption of the current generation and allowing them to use up most of the remaining CO_2 budget is unconstitutional as it leaves future generations with a high reduction burden, and exposes them to extensive losses of freedom [94]. The German government has set up a climate protection programme and is preparing a climate change adaptation strategy [95]. A national prevention plan is also in preparation, which, among other things, will introduce concrete measures against climate and environment-related health damage. The National Prevention Conference outlines tasks facing individual actors in this context [96]. A climate adaptation act will create a framework for implementing the national climate change adaptation strategy with measurable targets in cooperation with the federal states.

In 2008, the German government set the strategic framework with the German Strategy for Adaptation to Climate Change (Deutsche Klimaanpassungsstrategie, DAS), to counter the effects of climate change with a focus on 16 fields of action [97]. A network of all federal ministries and 28 higher

Basic public health functions will be severely challenged by climate change impacts.

federal authorities is involved. Measurable targets are being developed in many clustered topics, including health.

Most political activities related to climate change adaptation involve protection against heat. According to a resolution of the 93rd conference of German federal health ministers, heat-health action plans are to be drawn up in federal states and municipalities nationwide by 2025 [98]. The recommendations, which can be used as a model, were developed jointly by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection, the BMG and the federal states [99].

Even in the absence of concrete targets and measures on how the healthcare system can become climate-neutral and climate-resilient, some transformative action is evident at the level of healthcare actors and institutions. For example, the 125th German Medical Assembly called for a national strategy for climate-friendly healthcare [100]. In December 2022, the BMG, leading organisations in the health care sector, the federal states and municipal umbrella organisations signed the Climate Pact for Health and declared their intention to work together for adaptation and mitigation in the healthcare sector [101]. It is important to note that mandates in the German healthcare system are very heterogeneous, and responsibility is distributed in a complex manner among different levels and within the self-governance of involved actors.

Health must not be considered alone in the development and implementation of mitigation and adaptation measures; health must be considered in all departments in the sense of 'Health in all Policies'. Co-benefits are achieved through measures that are both good for the climate and the environment, and promise public health benefits through risk reduction or health promotion. In particular, the areas of renewable energy (reducing emissions and improving air quality), active rather than motorised mobility (reducing emissions, improving air quality, and increasing physical activity), and plant-based diets (reducing emissions and reducing non-communicable diseases) hold great potential for these co-benefits [102]. Because of the synergies between climate change adaptation, the improvement of human health, and biodiversity conservation, more partnerships should be formed between urban planning, landscape design, conservation, and health and other sectors.

5.4 Transformation toward a resilient public health system

It is apparent that a systemic view via the One Health or Planetary Health approaches is necessary for climate change adaptation and climate protection.

Brown and Westaway [103] describe how successfully dealing with adversity and challenges can entail a reorganisation or transformation of systems in which adaptive functions are optimised. The transformative consequence of resilient behaviour is also reflected in current thinking about environmental change and socioecological systems.

In particular, the WHO definition of resilience provides a comprehensive description in this context. The WHO defines resilience as the ability of a health system to prepare for, cope with, and learn from shock events, among other things, while maintaining the core functions of the health system [104]. Ideally, resilience is not a return to the original state, but an evolution to a better state [105].

A climate-resilient health system could be guided by internationally established Essential Public Health Functions.

Transformation as part of health system resilience can refer to the system's ability to change practices, re-design certain services or public health programs to be more accessible, or it can refer to medical and technological breakthroughs. Resilience at the system level can be strengthened by introducing new financing mechanisms; this can increase the economic sustainability of the system and its ability to anticipate and counter potential future crises.

In addition to enabling health systems to better cope with climate change-related challenges, health care institutions must also do their part to mitigate climate change. The healthcare sector contributes significantly to the emission of greenhouse gases worldwide. The healthcare sector's share of German greenhouse gas emissions ranges from 5.2% [106] to 6.7% [107], depending on the estimate. Currently, there is no legal obligation for standardised reporting of greenhouse gas emissions in the German healthcare sector. Only a few healthcare facilities document their emissions voluntarily [93].

Relevant areas for reducing the ecological footprint of hospitals, the pharmaceutical industry and other healthcare facilities include the manufacture and supply chains of drugs and medical devices, construction, energy supply, nutrition or communal catering, waste reduction and separation, climate-friendly alternatives in consumables (from anaesthetic gases to single-use instruments to office materials), and environmentally friendly workplace health promotion and occupational safety. Physicians enjoy a high degree of trust among the population and therefore have an important societal role to play in raising awareness and changing behaviour in favour of co-benefits, e.g. diets that emit little CO_2 and also promote health [108].

To address and adapt to the challenges of environmental determinants of health, an integrated and evidence-based approach is needed in healthcare, public health, and across sectors, informed by good governance, appropriate management mechanisms, high-level political will, and adequate human, technical, technological, and financial resources. The WHO is currently further developing approaches that incorporate climate change into health concepts, such as the Essential Public Health Functions (EPHFs), a model for assessing and developing public health structures and their functions [9, 109]. These core functions for public health provide guidance to public health systems; however, publications that apply to the European region have so far given too little consideration to environmental and climate aspects. The German Zukunftsforum Public Health (future forum on public health) published a ‘Call for and to Action: Climate Change and Public Health’ in the summer of 2022, which formulated recommendations for public health stakeholders and policy makers on this topic. The core functions of public health are addressed, but not yet fully formulated [110].

Although the public health core functions for Germany and Europe have not yet been formulated to include climate change and environmental aspects, the core functions of the Pan American Health Organization (PAHO) of the WHO already refer to climate resilience and sustainability [9]:

(1) Monitoring and evaluation of health and well-being, equity, and social determinants of health to determine their impact on environmental public health

(2) Environmental health surveillance of environmental hazards, exposures, health risks, and risk management measures

(3) Promotion and management of environmental health research and knowledge

(4) Development and implementation of environmental health policies and promotion of legislation in this area

(5) Participation and social mobilisation to promote communication and action on environmental determinants of health

(6) Development of human resources for environmental public health

(7) Use and management of essential medicines and health technologies in an environmentally safe and sustainable manner to protect public health

(8) Efficient and equitable financing of environmental public health

(9) Equitable access to health care facilities that are climate resilient and environmentally sustainable

(10) Equitable access to environmental public health interventions that promote health, reduce risk factors, and promote healthy behaviours

(11) Including the environmental public health dimension in the management and promotion of interventions on social determinants of health.

The complete elaboration of a concept on public health and environmental and climate factors is still pending. However, the individual articles and, in particular, the final article of this Status Report on Climate Change and Health can make a substantial contribution to this and use the preliminary work described. The following articles list recommendations for action, the implementation of which can reduce the impact of climate change for the public health sector. To conclude the series of articles, these recommendations will be revisited in a separate article and related to the public health core functions mentioned above in order to provide guidance to public health actors in strengthening the resilience of the healthcare system.

The authors of all the articles published in this series thus present an up-to-date, actionable report focused on Germany that stresses our ability to act in the face of the threats posed by climate change and provides actors with a solid basis for concrete action. The scientific evidence is overwhelming, the status report provides orientation – action must now be taken.

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References

1. Eis D, Helm D, Laußmann D et al. (2010) Klimawandel und Gesundheit. Ein Sachstandsbericht. Robert Koch-Institut, Berlin. https://www.rki.de/DE/Content/Gesund/Umwelteinfluesse/Klimawandel/Klimawandel-Gesundheit-Sachstandsbericht.html (As at 19.12.2022)
2. Nowossadeck E, von der Lippe E, Lampert T (2019) Developments in life expectancy in Germany. Current trends. J Health Monit 4(1):38–45 https://edoc.rki.de/handle/176904/5914 (As at 29.01.2023)
3. Statistisches Bundesamt (Destatis) (2022) Durchschnittliche Lebenserwartung (Periodensterbetafel) 2019/21 https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Sterbefaelle-Lebenserwartung/sterbetafel.html (As at 30.03.2023)
4. Imbery F, Kaspar F, Friedrich K et al. (2021) Klimatologischer Rückblick auf 2020: Eines der wärmsten Jahre in Deutschland und Ende des bisher wärmsten Jahrzents. Deutscher Wetterdienst, Offenbach. https://www.dwd.de/DE/leistungen/besondereereignisse/temperatur/20210106_rueckblick_jahr_2020.html (As at 19.12.2022)
5. Kemter M, Fischer M, Luna LV et al. (2021) Cascading hazards in the aftermath of Australia's 2019/2020 black summer wildfires. Earths Future 9(3):e2020EF001884
6. Kaspar-Ott I, Hertig E, Traidl-Hoffmann C et al. (2020) Wie sich der Klimawandel auf unsere Gesundheit auswirkt. Pneumo News 12(4):38–41
7. Pörtner HO, Scholes RJ, Agard J et al. (2021) IPBES-IPCC Co-sponsored workshop report on biodiversity and climate change. IPBES, IPCC. https://doi.org/10.5281/zenodo.4782538 (As at 19.12.2022)
8. World Health Organization (2021) 21st century health challenges: Can the essential public health functions make a difference? WHO, Geneva. https://www.who.int/publications/i/item/9789240038929 (As at 19.12.2022)
9. Pan American Health Organization (2022) The essential environmental public health functions. A framework to implement the agenda for the Americas on health, environment, and climate change 2021–2030. PAHO, Washington, D.C. https://iris.paho.org/handle/10665.2/55673 (As at 19.12.2022)
10. Bundesministerium für Bildung und Forschung (2022) Richtlinie zur Erforschung der Zusammenhänge zwischen Biodiversität und menschlicher Gesundheit – Ein Beitrag zur Forschungsinitiative zum Erhalt der Artenvielfalt. BMBF. https://www.bmbf.de/bmbf/shareddocs/bekanntmachungen/de/2022/08/2022–08-09-Bekanntmachung-Biodiversit%C3%A4t.html (As at 19.12.2022)
11. Ege MJ, Mayer M, Normand AC et al. (2011) Exposure to environmental microorganisms and childhood asthma. N Engl J Med 364(8):701–709

12. Riedler J, Braun-Fahrländer C, Eder W et al. (2001) Exposure to farming in early life and development of asthma and allergy: A cross-sectional survey. Lancet 358(9288):1129–1133

13. Daszak P, Amuasi J, das Neves CG et al. (2020) Workshop report on biodiversity and pandemics of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). IPBES, Bonn.
https://ipbes.net/sites/default/files/2020-12/IPBES%20Workshop%20on%20Biodiversity%20and%20Pandemics%20Report_0.pdf (As at 19.12.2022)

14. Kaplan S (1995) The restorative benefits of nature: Toward an integrative framework. J Environ Psychol 15(3):169–182

15. Ulrich RS, Simons RF, Losito BD et al. (1991) Stress recovery during exposure to natural and urban environments. J Environ Psychol 11(3):201–230

16. Akademie der Naturwissenschaften Schweiz (2019) Biodiversität, eine Garantie für Gesundheit? Swiss Academies Factsheets 14(3):1–10

17. Lovell R, Wheeler BW, Higgins SL et al. (2014) A systematic review of the health and well-being benefits of biodiverse environments. J Toxicol Environ Health B Crit Rev 17(1):1–20

18. Marselle MR, Stadler J, Korn H et al. (2019) Biodiversity and health in the face of climate change: Challenges, opportunities and evidence gaps. In: Marselle MR, Stadler J, Korn H et al. (Eds) Biodiversity and health in the face of climate change. Springer Nature, Cham, P. 1–13

19. Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: Synthesis. Island Press, Washington D.C.

20. Settele J (2020) Die Triple-Krise: Artensterben, Klimawandel, Pandemien: Warum wir dringend handeln müssen. Edel Books, Hamburg

21. Nesshöver C, Assmuth T, Irvine KN et al. (2017) The science, policy and practice of nature-based solutions: An interdisciplinary perspective. Sci Total Environ 579:1215–1227

22. Hunter RF, Cleary A, Braubach M (2019) Environmental, health and equity effects of urban green space interventions In: Marselle MR, Stadler J, Korn H et al. (Eds) Biodiversity and health in the face of climate change. Springer Nature, Cham, P. 381–409

23. Marselle MR, Bowler DE, Watzema J et al. (2020) Urban street tree biodiversity and antidepressant prescriptions. Sci Rep 10(1):22445

24. United Nations (2018) 2018 revision of world urbanization prospects. United Nations.
https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf (As at 10.03.2023)

25. IPCC (2021) Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pirani A 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.
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf (As at 14.02.2023)

26. Romanello M, McGushin A, Di Napoli C et al. (2021) The 2021 report of the Lancet Countdown on health and climate change: Code red for a healthy future. Lancet 398(10311):1619–1662

27. Romanello M, Di Napoli C, Drummond P et al. (2022) The 2022 report of the Lancet Countdown on health and climate change: Health at the mercy of fossil fuels. Lancet 400(10363):1619–1654

28. Szopa S, Naik V, Adhikary B et al. (2021) Short-lived climate forcers. In: Masson-Delmotte V, Zhai P, Pirani, A 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 (IPCC). IPCC, Cambridge.
https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-6/ (As at 19.12.2022)

29. Moss RH, Edmonds JA, Hibbard KA et al. (2010) The next generation of scenarios for climate change research and assessment. Nature 463(7282):747–756

30. Meinshausen M, Nicholls ZRJ, Lewis J et al. (2020) The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci Model Dev 13(8):3571–3605

31. Riahi K, van Vuuren DP, Kriegler E et al. (2017) The shared socio-economic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob Environ Change 42:153–168

32. Kahlenborn W, Porst L, Voß M (2021) Klimawirkungs- und Risikoanalyse für Deutschland 2021 (Kurzfassung). Umweltbundesamt (Ed) Climate Change 26/2021. https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/kwra2021_teilbericht_zusammenfassung_bf_211027_0.pdf (As at 17.01.2023)

33. Mücke HG, Matzarakis A (2017) Klimawandel und Gesundheit. In: Wichman HE, Fromme H (Eds) Handbuch der Umweltmedizin. ecomed Medizin, Landsberg, P. 1–38

34. Hambrecht E, Tolhurst R, Whittaker L (2022) Climate change and health in informal settlements: A narrative review of the health impacts of extreme weather events. Environ Urban 34(1):122–150

35. Bolte G, Dandolo L, Gepp S et al. (forthcoming) Climate change and health equity: A public health perspective on climate justice. J Health Monit. www.rki.de/jhealthmonit-en

36. Wolf M, Ölmez C, Schönthaler K et al. (2021) Klimawirkungs- und Risikoanalyse für Deutschland 2021, Teilbericht 5: Klimarisiken in den Clustern Wirtschaft und Gesundheit. Umweltbundesamt (Ed) Climate Change 24/2021. https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/kwra2021_teilbericht_5_cluster_wirtschaft_gesundheit_bf_211027_0.pdf (As at 20.12.2022)

37. World Health Organization (1986) Ottawa charter for health promotion, 1986. World Health Organization. Regional Office for Europe. https://www.who.int/publications/i/item/ottawa-charter-for-health-promotion (As at 12.05.2023)

38. Hertig E (2021) Klimawandel und Gesundheit in Europa. Geographische Rundschau 73(3–2021):4–7

39. Kaspar-Ott I, Hertig E (2022) Der Klimawandel: Wo wir stehen und was uns erwartet. In: Scherer M, Berghold J, Hierdeis H (Eds) Klimakrise und Gesundheit: Zu den Risiken einer menschengemachten Dynamik für Leib und Seele. Vandenhock & Ruprecht, Göttingen, P. 23–48

40. Ofori SA, Cobbina SJ, Obiri S (2021) Climate change, land, water, and food security: Perspectives from Sub-Saharan Africa. Front Sustain Food Syst 5: 680924

41. McIntyre KM, Setzkorn C, Hepworth PJ et al. (2017) Systematic assessment of the climate sensitivity of important human and domestic animals pathogens in Europe. Sci Rep 7(1):7134

42. Ibañez-Justicia A, Poortvliet PM, Koenraadth CJM (2019) Evaluating perceptions of risk in mosquito experts and identifying undocumented pathways for the introduction of invasive mosquito species into Europe. Med Vet Entomol 33(1):78–88

43. Semenza JC, Suk JE (2018) Vector-borne diseases and climate change: A European perspective. FEMS Microbiol Lett 365(2):fnx244

44. Beermann S, Dobler G, Faber M et al. (2023) Impact of climate change on vector- and rodent-borne infectious diseases. J Health Monit 8(S3):33–61. www.rki.de/jhealthmonit-en (As at 01.06.2023)

45. Fritsch U, Zebisch M, Voß M et al. (2021) Klimawirkungs- und Risikoanalyse für Deutschland 2021, Teilbericht 3: Klimarisiken im Cluster Wasser. Umweltbundesamt (Ed) Climate Change 22/2021. https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/kwra2021_teilbericht_3_cluster_wasser_bf_211027_0.pdf (As at 20.12.2022)

46. Loewe P, Frohse A, Schulz A (2009) Temperatur. In: Loewe P (Ed) System Nordsee – Zustand 2005 im Kontext langzeitlicher Entwicklungen. Bundesamt für Seeschifffahrt und Hydrographie, Hamburg und Rostock, P. 111–134. https://www.bsh.de/DE/PUBLIKATIONEN/_Anlagen/Downloads/Meer_und_Umwelt/Berichte-des-BSH/Berichte-des-BSH_44.html (As at 20.12.2022)

47. Matzarakis A, Tinz B (2014) Tourismus an der Küste sowie in Mittel- und Hochgebirge: Gewinner und Verlierer. In: Lozán JL, Graßl H, Jendritzky G et al. (Eds) Warnsignal Klima: Gefahren für Pflanzen, Tiere und Menschen. www.warnsignale.uni-hamburg.de, publ. electronically. https://www.klima-warnsignale.uni-hamburg.de/buchreihe/gesundheitsrisiken/kapitel-4–1-tourismus-an-der-kueste-sowie-in-mittel-und-hochgebirge-gewinner-und-verlierer/ (As at 20.12.2022)

48. German Federal Institute for Risk Assessment (2020) Is climate change increasing the risk of infection from vibrios? https://www.bfr.bund.de/cm/349/is-climate-change-increasing-the-risk-of-infectio-from-vibrios.pdf (As at 29.01.2023)

49. Semenza JC, Paz S (2021) Climate change and infectious disease in Europe: Impact, projection and adaptation. Lancet Reg Health Eur 9:100230

50. Meinke I (2020) Norddeutschland im Klimawandel – Was wissen wir über Klima, Klimawandel und Auswirkungen in Norddeutschland? Helmholtz-Zentrum, Geesthacht. https://www.hereon.de/imperia/md/content/klimabuero/klimaberichte/hzg_norddeutschland-im-klimawandel_e-book.pdf (As at 20.12.2022)

51. Dupke S, Buchholz U, Fastner J et al. (2023) Impact of climate change on waterborne infections and intoxications. J Health Monit 8(S3): 62–77. www.rki.de/jhealthmonit-en (As at 01.06.2023)

52. Kovats RS, Edwards SJ, Hajat S et al. (2004) The effect of temperature on food poisoning: A time-series analysis of salmonellosis in ten European countries. Epidemiol Infect 132(3):443–453

53. Dietrich J, Hammerl JA, Johne A et al. (2023) Impact of climate change on foodborne infections and intoxications. J Health Monit 8(S3): 78–92. www.rki.de/jhealthmonit-en (As at 01.06.2023)

54. Burnham JP (2021) Climate change and antibiotic resistance: A deadly combination. Ther Adv Infect Dis 8:2049936121991374

55. MacFadden DR, McGough SF, Fisman D et al. (2018) Antibiotic resistance increases with local temperature. Nat Clim Chang 8(6):510–514

56. Meinen A, Tomczyk S, Wiegand F et al. (2023) Antimicrobial resistance in Germany and Europe – A systematic review on the increasing threat accelerated by climate change. J Health Monit 8(S3): 93–108. www.rki.de/jhealthmonit-en (As at 01.06.2023)

57. Schultz MG, Klemp D, Wahner A (2017) Luftqualität. In: Brasseur GP, Jacob D, Schuck-Zöller S (Eds) Klimawandel in Deutschland: Entwicklung, Folgen, Risiken und Perspektiven. Springer, Berlin, Heidelberg, P. 127–136

58. Jacob DJ, Winner DA (2009) Effect of climate change on air quality. Atmos Environ 43(1):51–63

59. Katragkou E, Zanis P, Kioutsioukis I et al. (2011) Future climate change impacts on summer surface ozone from regional climate-air quality simulations over Europe. J Geophys Res Atmos 116:D22307

60. Hertig E, Schneider A, Peters A et al. (2019) Association of ground-level ozone, meteorological factors and weather types with daily myocardial infarction frequencies in Augsburg, Southern Germany. Atmos Environ 217:116975

61. Katsouyanni K, Samet JM, Anderson HR et al. (2009) Air pollution and health: A European and North American approach (APHENA). Res Rep Health Eff Inst 142:5–90

62. Hertig E, Russo A, Trigo RM (2020) Heat and ozone pollution waves in Central and South Europe – Characteristics, weather types, and association with mortality. Atmosphere 11(12):1271

63. Jahn S, Hertig E (2020) Modeling and projecting health-relevant combined ozone and temperature events in present and future Central European climate. Air Qual Atmos Health 14:563–580

64. Breitner-Busch S, Mücke HG, Schneider A et al. (forthcoming) Impact of climate change on non-communicable diseases due to increased ambient air pollution. J Health Monit. www.rki.de/jhealthmonit-en

65. Matzarakis A (2021) Hitzeereignisse: Charakteristika, Gesundheitsrelevanz und Anpassungsmöglichkeiten. Geographische Rundschau 73(3–2021):8–13

66. Winklmayr C, Muthers S, Niemann H et al. (2022) Hitzebedingte Mortalität in Deutschland zwischen 1992 und 2021. Dtsch Arztebl Int 119(26):451–457

67. Schlegel I, Muthers S, Matzarakis A (2021) Einfluss des Klimawandels auf die Morbidität und Mortalität von Atemwegserkrankungen. Umweltbundesamt (Ed) Umwelt & Gesundheit 04/2021. https://www.umweltbundesamt.de/en/publikationen/einfluss-des-klimawandels-auf-die-morbiditaet (As at 20.12.2022)

68. Winklmayr C, Matthies-Wiesler F, Muthers S et al. (forthcoming) Heat in Germany: Health risks and preventive measures. J Health Monit. www.rki.de/jhealthmonit-en

69. Razafimaharo C, Krähenmann S, Höpp S et al. (2020) New high-resolution gridded dataset of daily mean, minimum, and maximum temperature and relative humidity for Central Europe (HYRAS). Theor Appl Climatol 142(3):1531–1553

70. Kreienkamp F, Philip SY, Tradowsky JS et al. (2021) Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021. World Weather Attribution https://www.worldweatherattribution.org/wp-content/uploads/Scientific-report-Western-Europe-floods-2021-attribution.pdf (As at 20.12.2022)

71. Thober S, Marx A, Boeing F (2018) Auswirkungen der globalen Erwärmung auf hydrologische und agrarische Dürren und Hochwasser in Deutschland. Helmholtz-Zentrum für Umweltforschung GmbH, Leipzig. https://www.ufz.de/export/data/2/207531_HOKLIM_Brosch%C3%BCre_final.pdf (As at 20.12.2022)

72. UFZ Helmholtz Zentrum für Umweltforschung (2022) Dürremonitor Deutschland – Jährliche Dürrestärken in Deutschland. https://www.ufz.de/index.php?de=47252 (As at 20.12.2022)

73. Riedel T, Nolte C, aus der Beek T et al. (2021) Niedrigwasser, Dürre und Grundwasserneubildung – Bestandsaufnahme zur gegenwärtigen Situation in Deutschland, den Klimaprojektionen und den existierenden Maßnahmen und Strategien. Umweltbundesamt (Ed) Texte 174/2021. https://www.umweltbundesamt.de/publikationen/niedrigwasser-duerre-grundwasserneubildung (As at 20.12.2022)

74. Butsch C, Beckers LM, Nilson E et al. (forthcoming) Health impacts of extreme weather events – Cascading risks in a changing climate. J Health Monit. www.rki.de/jhealthmonit-en

75. Ludwig A, Bayr D, Pawlitzki M et al. (2021) Der Einfluss des Klimawandels auf die Allergenexposition: Herausforderungen für die Versorgung von allergischen Erkrankungen. In: Günster C, Klauber J, Robra B-P et al. (Eds) Versorgungsreport Klima und Gesundheit. MWV Medizinisch Wissenschaftliche Verlagsgesellschaft mbH & Co. KG, Berlin, P. 133–144. https://www.wido.de/publikationen-produkte/buchreihen/versorgungs-report/klima-und-gesundheit/ (As at 20.12.2022)

76. Seth D, Bielory L (2021) Allergenic pollen season variations in the past two decades under changing climate in the United States. Immunol Allergy Clin North Am 41(1):17–31

77. Lake IR, Jones NR, Agnew M et al. (2017) Climate change and future pollen allergy in Europe. Environ Health Perspect 125(3):385–391

78. Bergmann KC, Brehler R, Endler C et al. (forthcoming) Impact of climate change on allergic diseases in Germany. J Health Monit. www.rki.de/jhealthmonit-en

79. Baldermann C, Lorenz S (2019) UV-Strahlung in Deutschland: Einflüsse des Ozonabbaus und des Klimawandels sowie Maßnahmen zum Schutz der Bevölkerung. Bundesgesundheitsbl 62(5):639–645

80. Deutsche Krebsgesellschaft, Deutsche Krebshilfe, AWMF (2021) S3-Leitlinie Prävention von Hautkrebs Leitlinienprogramm Onkologie. DKG, DK, AWMF. https://www.leitlinienprogramm-onkologie.de/leitlinien/hautkrebs-praevention/ (As at 20.12.2022)

81. Baldermann C, Laschewski G, Grooß JU (forthcoming) Impact of climate change on non-communicable diseases caused by altered UV radiation. J Health Monit. www.rki.de/jhealthmonit-en

82. Clayton S, Manning CM, Speiser M et al. (2021) Mental health and our changing climate: Impacts, inequities, responses. American Psychological Association, and ecoAmerica, Washington, D. C. https://www.apa.org/news/press/releases/mental-health-climate-change.pdf (As at 21.12.2022)

83. Cianconi P, Betrò S, Janiri L (2020) The impact of climate change on mental health: A systematic descriptive review. Front Psychiatry 11:74

84. Gebhardt N, van Bronswijk K, Bunz M et al. (forthcoming) Scoping review of climate change and mental health in Germany – Direct and indirect impacts, vulnerable groups, resilience factors. J Health Monit. www.rki.de/jhealthmonit-en

85. Doyle U, Schröder P, Schönfeld J et al. (2020) Was ist der One Health-Ansatz und wie ist er umzusetzen? UMID 02/2020:65–72

86. Schwabe C (1964) Veterinary medicine and human health. Williams & Wilkins, Baltimore

87. Zinsstag J, Schelling E, Waltner-Toews D et al. (2011) From "one medicine" to "one health" and systemic approaches to health and well-being. Prev Vet Med 101(3–4):148–156

88. Gruetzmacher K, Karesh WB, Amuasi JH et al. (2021) The Berlin principles on one health – Bridging global health and conservation. Sci Total Environ 764:142919

89. One Health High-Level Expert P, Adisasmito WB, Almuhairi S et al. (2022) One Health: A new definition for a sustainable and healthy future. PLoS Pathog 18(6):e1010537

90. Zinsstag J, Crump L, Schelling E et al. (2018) Climate change and One Health. FEMS Microbiol Lett 365(11):fny085

91. Müller O, Jahn A, Gabrysch S (2018) Planetary Health: Ein umfassendes Gesundheitskonzept. Dtsch Arztebl 115(40):A 1751–1752

92. Baltruks D, Gepp S, van de Pas R et al. (2022) Gesundheit innerhalb planetarer Grenzen. Offene Fragen an Politik, Wissenschaft und Gesundheitsakteure. Centre for Planetary Health Policy. https://cphp-berlin.de/policy-brief-gesundheit-innerhalb-planetarer-grenzen/ (As at 20.12.2022)

93. Matthies-Wiesler F, Herrmann M, Schulz C et al. (2021) The Lancet countdown on health and climate change policy brief für Deutschland. https://www.klimawandel-gesundheit.de/wp-content/uploads/2021/10/20211020_Lancet-Countdown-Policy-Germany-2021_Document_v2.pdf (As at 20.12.2022)

94. Bundesverfassungsgericht (2021) Verfassungsbeschwerden gegen das Klimaschutzgesetz teilweise erfolgreich. Pressemitteilung Nr. 31/2021 vom 29. April 2021. https://www.bundesverfassungsgericht.de/SharedDocs/Pressemitteilungen/DE/2021/bvg21–031.html (As at 20.12.2022)

95. Die Bundesregierung (2022) Sofortprogramm 2022. https://www.bundesregierung.de/breg-de/suche/sofortprogramm-klimaschutz-1934852 (As at 20.12.2022)

96. Die Nationale Präventionskonferenz (2022) Prävention, Gesundheits-, Sicherheits- und Teilhabeförderung in Lebenswelten im Kontext klimatischer Veränderungen. https://www.npk-info.de/fileadmin/user_upload/umsetzung/pdf/gesundheits-_sicherheits-_und_teilhabefoerderung_in_lebenswelten_im_kontext_klimatischer_veraenderungen.pdf (As at 17.01.2023)

97. Die Bundesregierung (2008) Deutsche Anpassungsstrategie an den Klimawandel. https://www.bmu.bund.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/das_gesamt_bf.pdf (As at 07.03.2023)

98. Gesundheitsministerkonferenz (2020) Beschlüsse der GMK 30.09.2020–01.10.2020. https://www.gmkonline.de/Beschluesse.html?id=1018&jahr=2020 (As at 20.12.2022)

99. Bund/Länder Ad-hoc Arbeitsgruppe Gesundheitliche Anpassung an die Folgen des Klimawandels (2017) Handlungsempfehlungen für die Erstellung von Hitzeaktionsplänen zum Schutz der menschlichen Gesundheit. Bundesgesundheitsbl 60(6):662–672

100. Bundesärztekammer (2021) Ärztetag für Klimaneutralität des Gesundheitswesens bis 2030. https://www.bundesaerztekammer.de/presse/aktuelles/detail/aerztetag-fuer-klimaneutralitaet-des-gesundheitswesens-bis-2030 (As at 20.12.2022)

101. Bundesministerium für Gesundheit (2022) Gemeinsame Erklärung Klimapakt Gesundheit. Gemeinsam für Klimaanpassung und Klimaschutz im Gesundheitswesen eintreten. https://www.bundesgesundheitsministerium.de/fileadmin/Dateien/3_Downloads/G/Gesundheit/Erklaerung_Klimapakt_Gesundheit_A4_barrierefrei.pdf (As at 20.12.2022)

102. Haines A (2017) Health co-benefits of climate action. Lancet Planet Health 1(1):e4–e5

103. Brown K, Westaway E (2011) Agency, capacity, and resilience to environmental change: Lessons from human development, well-being, and disasters. Annu Rev of Environ Resour 36(1):321–342

104. World Health Organization (2022) Health systems resilience toolkit: A WHO global public health good to support building and strengthening of sustainable health systems resilience in countries with various contexts. WHO, Geneva. https://www.who.int/publications/i/item/9789240048751 (As at 20.12.2022)

105. European Observatory on Health Systems and Policies (2020) How to make health systems more resilient to COVID-19 and other crises. News Release 19.06.2020. https://eurohealthobservatory.who.int/news-room/news/item/19–06-2020-how-to-make-health-systems-more-resilient-to-covid-19-and-other-crises (As at 20.12.2022)

106. Karliner J, Slotterback S, Boyd R et al. (2019) Health Care's Climate Footprint. How the health sector contributes to the global climate crisis and opportunities for action. Health Care Without Harm, Arup. https://noharm-global.org/sites/default/files/documents-files/5961/HealthCaresClimateFootprint_092319.pdf (As at 20.12.2022)

107. Pichler PP, Jaccard IS, Weisz U et al. (2019) International comparison of health care carbon footprints. Environ Res Lett 14(6):064004

108. Betsch C, Eitze S, Sprengholz P et al. (2022) Ergebnisse aus der Planetary Health Action Survey – PACE. Universität Erfurt – Philosophische Fakultät. https://projekte.uni-erfurt.de/pace/_files/PACE_W07–09.pdf (As at 20.12.2022)

109. Frumkin H, Hess J, Luber G et al. (2008) Climate change: the public health response. Am J Public Health 98(3):435–445

110. Zukunftsforum Public Health (2022) Call for and to Action: Klimawandel und Public Health. https://zukunftsforum-public-health.de/call-for-action-klimawandel/ (As at 20.12.2022)

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Impact of climate change on vector- and rodent-borne infectious diseases

Abstract

Background: Endemic and imported vector- and rodent-borne infectious agents can be linked to high morbidity and mortality. Therefore, vector- and rodent-borne human diseases and the effects of climate change are important public health issues.

Methods: For this review, the relevant literature was identified and evaluated according to the thematic aspects and supplemented with an analysis of surveillance data for Germany.

Results: Factors such as increasing temperatures, changing precipitation patterns, and human behaviour may influence the epidemiology of vector- and rodent-borne infectious diseases in Germany.

Conclusions: The effects of climatic changes on the spread of vector- and rodent-borne infectious diseases need to be further studied in detail and considered in the context of climate adaptation measures.

This is part of a series of articles that constitute the German Status Report on Climate Change and Health 2023.

CLIMATE CHANGE · RESERVOIR HOSTS · VECTORS · ARBOVIRUSES · ZOONOSES · PUUMALA ORTHOHANTAVIRUS

1. Introduction

Vector- and rodent-borne human diseases and the impact that climatic changes may have on them are an important public health issue regionally, nationally, and globally. Both native and imported vector- and rodent-borne infectious agents can be linked to high morbidity and mortality and impose significant costs on the health care system. Globalisation and climate change also favour the introduction and spread of new vectors and new vector-borne infectious agents, which are accompanied by an expansion of the infectious agent spectrum in Germany.

This article provides an overview of these factors as well as an outlook on possible developments regarding different vector- and rodent-borne diseases that could be influenced by climate change (Figure 1). The first part of the article focuses on mosquito-borne viruses, which have regained importance in Germany as a consequence of globalisation and climate change. The next section considers tick-borne pathogens and the diseases they cause, including tick-borne encephalitis (TBE) and Lyme disease, which have high public health relevance for Germany. In the subsequent section, the zoonotic hantavirus disease in humans is described.

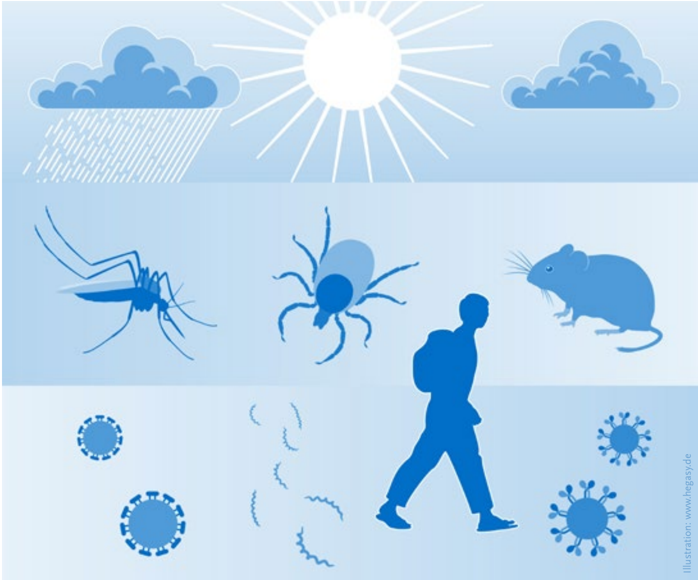


Figure 1
The climate (top) influences vectors and reservoir hosts as well as human behaviour (middle) and thereby vector- and rodent-borne pathogens (bottom) and the infectious diseases they cause
Illustration: Guido Hegasy

The final section lists recommendations for dealing with vector- and rodent-borne infections as well as for their control and prevention.

2. Methods

The authors jointly determined the content to be presented in this review according to their expertise. Relevant literature was identified according to the thematic aspects. In addition, reporting data collected at the Robert Koch Institute (RKI, Germany's national public health institute) in accordance with the German Protection against Infection Act (Infektionsschutzgesetz, IfSG) were included to illustrate the situation in Germany. Individual groups of authors prepared drafts for the various sections, which were discussed and finalised by all authors.

3. Infectious diseases associated with mosquitoes

3.1 Occurrence and distribution of vector-competent mosquitoes in Germany

Mosquitoes can be vectors of viruses, protozoa and filariae. Until a few decades ago, they were known in Germany only as vectors of plasmodia (parasitic protozoa), the causative agents of malaria. After the widespread eradication of malaria from Europe in the mid-20th century, mosquitoes did not play a role as vectors that needed to be monitored in Germany for a long time. The successful control of malaria was largely based on the development of synthetic drugs and the newly recognised insecticidal activity of DDT (dichlorodiphenyltrichloroethane) [1]. Mosquito-borne diseases characterised by relevant morbidity or even mortality were subsequently absent for decades. While the endemic *Plasmodium* species disappeared thanks to malaria control measures, the populations of the transmitting *Anopheles* species recovered and are still part of the present German mosquito fauna. This is composed of at least 52 species, with floodwater mosquitoes (*Aedes* (*Ae.*) *vexans, Ae. sticticus*) and the species of the *Culex* (*Cx.*) *pipiens* complex (*Cx. pipiens, Cx. torrentium*) being the most common and widespread mosquito species in Germany [2]. Five of these species are neozoa, i.e. species newly established in an area due to human influence, whose occurrence has been observed since 2007 as a consequence of globalisation and global warming. Continuous reproduction and repeated overwintering have been demonstrated for these species in Germany in the recent past, so that they must be regarded as established, at least regionally.

Since 2011, monitoring activities have been carried out continuously in Germany to provide up-to-date data on the occurrence and distribution of mosquito species. These are based both on the systematic recording of adults using trap catches and undirected larval collection (active monitoring), and on random submissions of mosquitoes from the public via the citizen science project 'Mückenatlas' (Mosquito Atlas, passive monitoring). In particular, the Mosquito Atlas has proven to be a good early warning system for detecting invasive species [3, 4].

For 23 of the species occurring in Germany, there is evidence that they are vector-competent for various pathogens, i. e. genetically and physiologically capable, in principle, of reproducing the pathogens in their bodies or bringing them to further development and transmitting them. This is also assumed to be the case for other native mosquito species, although reliable scientific evidence is still lacking [4].

The actual vector role of a blood-feeding arthropod is reflected by its vector capacity, which is, among other things, a function of vector frequency and the availability of infection sources [5]. Infection sources can be any vertebrates through which mosquitoes can become infected. The external temperature also plays a significant role in vector capacity, influencing both the development of the vector and of the pathogen inside the vector. At certain species-specific minimum temperatures, physiological processes are set in motion that accelerate with higher temperatures – up to maximum threshold temperatures. For example, after winter dormancy, some mosquito species continue larval development in spring at only a few degrees above freezing temperature (e. g. at 4 to 5°C for the Asian bush mosquito, *Ae. japonicus* [6]). With rising temperatures, there is an increase in biting frequency, acceleration of blood digestion, egg production, juvenile development, and generation cycle, resulting in higher overall population densities. Similarly, seasonal mosquito activity is extended. Counteracting this is a shorter individual lifespan at high temperatures [7].

Most arboviruses, i. e. viruses transmitted by arthropods, replicate and disseminate in their vectors only above temperatures of 11 to 15°C [8]. Within the tolerable temperature range of vectors and viruses, virogenesis runs faster the higher the temperature, so that the intensity and efficiency of pathogen transmission increases with higher mosquito biting frequency [9]. The fact that virus transmission by mosquitoes so far has been uncommon in Germany is possibly due – apart from the presumably moderate availability of infection sources – to the fact that temperatures have not been sufficiently high for the development of viruses in the vector and their efficient transmission. This is supported by laboratory experiments in which infected mosquito species in temperate climates became infectious at incubation temperatures of 24 to 27°C [10–12]. The first appearance of West Nile virus (WNV) in 2018, the warmest year to date since weather records began in Germany [13], also supports this hypothesis. Rising temperatures could thus enable the transmission of pathogens not only by known potential vectors, but also by native mosquito species not yet recognised as potential vectors.

Potential vectors of WNV, various *Culex* and *Aedes* species, occur throughout Germany [14]. The virus circulates seasonally between mosquitoes and birds, which carry the virus (transport hosts), develop a high viral load in the

International tourism and global trade in animals and goods contribute to the spread of vectors and pathogens.

blood (viraemia), thus acting as amplification hosts, and sometimes die of the infection [15]. Based on previous outbreaks in southern Europe, cases of WNV infection had therefore been expected in Germany long before 2018 [16, 17]. Apparently, only the particularly high temperatures in late summer 2018 enabled efficient virus development in mosquitoes and visible transmission in the form of disease cases.

The main vectors of WNV to mammals, transmitting the virus from birds to other host groups (bridge vectors), are certain variants of the common house mosquito *Cx. pipiens*, especially late summer hybrids of the two biotypes *pipiens* and *molestus*, which do not discriminate between avian and mammalian hosts [18]. However, mammals themselves are not sources of WNV infection for mosquitoes (dead-end hosts) because the viral load in their blood is too low for viruses to be passed to mosquitoes. Since 2019, WNV has been detected several times in mosquitoes of the *Cx. pipiens* complex in Germany during the mosquito season and also in hibernating females of this species complex in the winter of 2020/2021 [19]. This proves the overwintering of the virus in the vectors and suggests its long-term persistence in Germany.

Due to evolutionary adaptation, endemic mosquito species cope well with the central European climate and can survive cold winters without any problems. Presence of infection sources, sufficient precipitation and availability of water reservoirs for larval development, species that have not yet appeared as vectors could also become relevant in the medium term if climate change and associated warming continues. Availability of water reservoirs is likely, especially in residential areas, due to the storage of rainwater in artificial containers for garden irrigation. In the long term, it must be assumed that mosquito species closely adapted to temperate conditions will shift their ranges to cooler regions and be replaced by species that prefer a warm climate.

Among the five new mosquito species that have become established in Germany since 2007, three are thermophilic (*Ae. albopictus, Anopheles petragnani, Culiseta longiareolata*) and three species are considered potential vectors of human pathogens (*Ae. albopictus, Ae. japonicus, Ae. koreicus*) [20]. As a result of poor climatic adaptation, thermophilic species find it difficult to establish and spread. Geographically, they occur only locally in Germany. However, their presence indicates improving living conditions for thermophilic species. Among these, the Asian tiger mosquito *Ae. albopictus* has a prominent position: it is considered the most invasive mosquito species worldwide [21] and is a highly efficient vector of numerous human pathogens [22, 23] (Section 3.3 Pathogens transmitted by *Ae. albopictus*). In southern Europe, where this mosquito is widespread and regionally occurs at high densities, it has been observed as a vector of dengue virus (DENV) and chikungunya virus (CHIKV) on several occasions [24].

The intercontinental spread of the tiger mosquito to Europe is mainly facilitated by the used tyre trade; its entry into Germany, however, is probably mainly due to long-distance motor vehicle traffic from southern Europe [25, 26]. Several populations have been established in Germany [27]. These can be traced back to strains that have adapted to climatic conditions and – in contrast to tropical strains – produce diapausing eggs, i. e. eggs characterised by a physiological resting phase enabling them to overwinter.

Table 1
Important potential mosquito vectors in Germany and their epidemiological significance for the transmission of selected viruses

	WNV	DENV	CHIKV	ZIKV	USUV	SINV
Aedes albopictus (Asian tiger mosquito)	+	+++	+++	+++	?	+
Aedes japonicus (Asian bush mosquito)	+	+	+	+	+	?
Aedes koreicus (Korean bush mosquito)	?	?	+	+	?	?
Aedes vexans	+	?	?	+	?	?
Culex pipiens (common house mosquito)	+++	–	–	–	+++	+++
Culex modestus	++	?	?	–	?	?
Culex torrentium	+	?	?	–	++	+

+++ = high, ++ = medium, + = low, – = no, ? = unknown epidemiological significance
WNV=West Nile virus, DENV=dengue virus, CHIKV=chikungunya virus, ZIKV=Zika virus, USUV=Usutu virus, SINV=Sindbis virus

Populations are predominantly found in the relatively warm Upper Rhine Valley and other areas of Baden-Württemberg, with Hesse, Bavaria and Thuringia also being affected [28].

In most places with known tiger mosquito populations, prevention and control measures have been implemented by (local) authorities (e.g. [29]). The primary goal of these measures is no longer the elimination of populations, but the reduction of population densities, as these determine the risk of pathogen transmission. Since mosquitoes have not been a health problem in central Europe in recent decades, expertise in vector management is currently very limited in Germany.

With increasing temperatures, the Asian tiger mosquito should find it easier to settle and spread in Germany. According to the literature, the limiting factor for settlement is the average annual temperature, which must be at least 11°C [30, 31]. Cold winters also cause problems for this mosquito; however, enough eggs usually survive in sheltered places and manage to establish a new population in the following year [32, 33]. According to the latest models, most areas in Germany will be suitable for *Ae. albopictus* colonisation by the year 2040, although different modelling approaches (e.g. mechanistic models, correlative niche models) lead to different outcomes. Lack of knowledge of climatic requirements and ecological adaptability of the tiger mosquito allow only rough predictions [34, 35]. The strongest limiting factors for the spread of *Ae. albopictus* in Europe are low winter minimum temperatures in the east, low summer average temperatures in the centre, and low precipitation in the south [36].

Ae. japonicus and *Ae. koreicus*, which have been shown to be able to transmit some viruses and nematodes in experimental studies [37–39], have also regionally established in Germany. They have not yet appeared as vectors in the field. Table 1 shows important mosquito species occurring in Germany that can act as vectors.

3.2 Pathogens transmitted by native mosquitoes

Some mosquito-borne viruses circulating in Germany, such as Sindbis, Batai, or Usutu viruses, are only mildly pathogenic or epidemiologically negligible, but the recently emerging WNV is of relevant public health importance. It belongs to the family *Flaviviridae* and was first isolated from a febrile patient in Uganda in 1937. Since the 1950s, it has been detected in mosquitoes, birds, and humans in many European countries [16]. An outbreak in Romania in 1996 was the first time it was associated with severe human illness and death in Europe [40]. In the last twenty years, increased epidemics have occurred on almost all continents [41].

During the hot summer of 2018, Europe experienced the largest recorded WNV outbreak to date, with more than 1,600 cases, including 166 deaths [42]. In contrast to previous large epidemics caused by WNV lineage 1 [16], WNV lineage 2 has been primarily circulating in Europe since 2010. Despite intensive and repeated investigations on the presence of WNV in German mosquitoes, birds, and horses, the virus was not detected in Germany until 2018 [13]. The same year saw the first reported human infection acquired in Germany (autochthonous infection); however, this infection was probably caused by direct contact with a dead bird. Human infection with WNV, as with all arboviruses, has been notifiable according to IfSG since 2016. In addition, there are overlapping notification requirements according to the German Transfusion Act (Transfusionsgesetz, TFG) [43]. Until 2017, all WNV infections reported in Germany were travel-associated. From 2019 to 2021, a total of 31 autochthonous human WNV infections were recorded in four German states (Berlin, Brandenburg, Saxony-Anhalt, and Saxony), with all of them presumably associated with mosquito bites (Table 2). All persons affected resided in regions where WNV infections in birds or horses had previously been described. Of these, 29 were symptomatic and thus fulfilled the reference definition of the RKI. The respective onset of disease was between July 27 and September 19, i.e. in or shortly after the hottest phases of the summer in the region. Ten women and 21 men aged 24 to 85 years were affected. Twelve infected persons had neuroinvasive infections, and of these, one patient died.

An estimated 80% of all WNV infections in humans are asymptomatic and about 19% develop West Nile fever without complications. About 1% of infected individuals develop a neuroinvasive form of the disease associated with a lethality of about 10%, predominantly the elderly and chronically ill [44]. The virus is also of great importance for blood

Table 2
Notifications of human West Nile virus infections since autochthonous emergence of the virus in Germany, 2018–2021
Source: SurvNet, database of infectious diseases with mandatory notification requirement in Germany

	Type of infections	2018	2019	2020	2021	Total
Notification according to IfSG	Travel-associated cases[1]	10	7	1	1	19
	Autochthonous cases[1]	1	5	20	4	30
	Autochthonous asymptomatic infections	0	0	2	0	2
Notification according to TFG only	Autochthonous infections in blood donors.	Not recorded	Not recorded	8	1	9
	Total	**11**	**12**	**31**	**6**	**60**

[1]Symptomatic infections
IfSG=German Protection against Infection Act, TFG=German Transfusion Act

Factors like increasing temperatures, changing precipitation patterns, and human behaviour may influence the incidence and prevalence of vector- and rodent-borne infectious diseases.

safety [45], as individuals requiring transfusions are more susceptible to severe WNV disease due to their underlying conditions.

Only parts of Germany are currently affected by autochthonous WNV transmission, mainly Berlin, large parts of Brandenburg, Saxony and Saxony-Anhalt, as well as smaller parts of Thuringia and Lower Saxony [43]. This area, defined by virus detections in humans, birds, mosquitoes, or horses, has hardly changed since 2018 but may expand at any time. The infection is only seasonally relevant, in Germany mainly in the period from July to September.

The exact routes by which WNV reached Germany are not known; however, closely related virus strains circulate in Austria and the Czech Republic [13]. It is possible that the very intense 2018 WNV season in southern Europe provided increased opportunities for expansion of the endemic area. Good conditions for WNV circulation between mosquitoes and birds due to the exceptionally long and hot summer of 2018 probably allowed the first overwintering to occur in Germany [13].

Hotter summers, changing precipitation patterns, and people's recreational behaviour may influence the epidemiology of WNV in Germany: observed seasonality in Germany and data on outbreaks in other regions indicate that longer and hotter summers result in longer and more intense seasonal transmission of WNV. Precipitation patterns can influence populations of WNV-transmitting mosquitoes and thus contribute locally and regionally to the intensification of WNV transmission [46]. Last but not least, during particularly long and hot summers, people tend to spend more time outdoors and may come into contact with WNV-transmitting mosquitoes with a higher probability. A possible compensatory effect is that travel-associated WNV infections and other travel-associated arbovirus infections may become less frequent when summer vacations are spent in Germany instead of abroad due to warmer weather.

Preventive approaches are professional vector control, personal protective measures to reduce the risk of exposure (especially for older persons and people with pre-existing conditions), and screening of blood donations. Vaccines against WNV are currently not available for humans. Improved target group-oriented education is needed to raise people's awareness of WNV, allowing them to take personal measures.

3.3 Pathogens transmitted by *Ae. albopictus*

In addition to the yellow fever mosquito *Ae. aegypti*, the Asian tiger mosquito is the most important vector for arboviruses in the tropics and subtropics, including DENV, CHIKV and Zika virus (ZIKV), which are diagnosed quite frequently in travellers returning to Germany.

DENV infection leads to clinical symptoms in about 25% of cases. Most patients have a mild febrile and self-limiting illness known as dengue fever. A small proportion of patients develop a severe form of the disease, which may be associated with bleeding. Most ZIKV infections are asymptomatic. When symptoms do occur, they are usually mild and similar to those of a DENV infection. ZIKV infections during pregnancy, however, can result in foetal malformations (e.g. microcephaly). CHIKV infection often manifests as chikungunya fever. The main symptoms are severe muscle and joint pains, which can lead to a painfully hunched posture. In 5 to 10% of sufferers, joint pain can last for months.

The endemic areas of these viruses are located in the tropics and subtropics, including popular travel destinations such as Thailand, India and Brazil. Table 3 shows the number of infections with these pathogens reported annually to the RKI in Germany, in accordance with IfSG, over the last ten years. The case numbers fluctuate strongly, influenced by varying infection risks in the travel destinations. Except for one hospital-acquired (nosocomial) DENV infection and three ZIKV infections in the context of laboratory accidents, all infections were travel-associated.

Local *Ae. albopictus* can transmit viruses from symptomatic or even asymptomatic viraemic travellers returning to Germany to other people. This has led to CHIKV epidemics in Italy and small autochthonous case clusters of DENV and ZIKV infections in other southern European countries [47–49].

Mosquito-borne autochthonous infections with supposedly tropical viruses have not yet been documented in Germany. However, vector competence studies with German *Ae. albopictus* populations show that they are capable of transmitting CHIKV under prevailing summer temperatures [50]. In contrast, common central European summer temperatures are probably not sufficient for DENV and ZIKV epidemics [51, 52]. Warmer summers and prolonged hot spells are likely to promote autochthonous transmission of the aforementioned pathogens, as are years with an early, warm spring in combination with a summer that is not too dry, leading to high mosquito densities in mid-summer. The importance of an early, warm spring was highlighted by autochthonous dengue clusters in France in 2022 [53]. It should be noted, for example, that up to 75% of infections with DENV are asymptomatic and are therefore rarely diagnosed in Germany, while the infected individuals may still be relevant as a source of virus for mosquitoes. Reported infections with these pathogens must therefore be regarded as the tip of the iceberg. However, travellers who are no longer viraemic on arrival in Germany, who arrive in the cold season, or who have visited areas without *Ae. albopictus* (or other suitable vectors) do not represent a virus source for local mosquitoes.

4. Infectious diseases associated with hard ticks

4.1 Hard ticks as vectors in Germany and the influence of environmental and climatic factors

In central Europe, hard ticks are the most important vectors of infectious agents to humans. Among the at least 19 hard tick species native to Germany, which live in natural

Table 3
Notifications of infections with dengue, chikungunya and Zika virus in Germany according to the German Protection against Infection Act, 2012–2021
Source: SurvNet, database of infectious diseases with mandatory notification requirement in Germany

	2012	2013	2014	2015	2016	2017	2018	2019	2020[2]	2021[2]
DENV	616	878	625	725	957	635	612	1176	205	60
CHIKV	9	16	162	110	74	33	26	88	26	4
ZIKV	0[1]	0[1]	0[1]	2[1]	22	69	18	11	6	2

[1] No IfSG reporting obligation yet, [2] Pandemic-related decline in long-distance travel activity
DENV=dengue virus, CHIKV=chikungunya virus, ZIKV=Zika virus, IfSG=German Protection against Infection Act

biotopes near suitable hosts, the castor bean tick *Ixodes (I.) ricinus* is most widespread throughout Germany and has the greatest significance for public health [54, 55]. This tick species is adapted to a very broad host range to ingest blood, finds particularly suitable conditions in oak-beech and mixed deciduous forests, in which it often occurs in high densities. All stages can feed on humans, although the juvenile stages in particular, with a size of about one millimetre, are easily overlooked. In addition, the meadow tick *Dermacentor (D.) reticulatus* and the ornate sheep tick *D. marginatus* are relatively widespread in some regions. The juvenile stages of these ticks usually parasitise rodents and can be detected in rodent burrows, their adults prefer larger mammalian hosts. Native hard ticks can transmit diverse pathogens such as TBE virus (Section 4.2 Tick-borne encephalitis), spirochaete bacteria of the genus *Borrelia* (Section 4.3 Lyme borreliosis), and other hitherto less noticed bacteria such as *Francisella tularensis (*causative agent of tularaemia), *Coxiella burnetii* (causative agent of Q fever), *Rickettsia* spp., *Anaplasma phagocytophilum, Ehrlichia* spp. and parasites such as *Babesia* spp. (e.g. causative agent of 'canine malaria' *Babesia canis*). Some of these pathogens cause more severe courses of disease and are therefore mostly notifiable in Germany according to IfSG or ordinances of the federal states. For others, cases of transmission to humans are recorded comparatively rarely, and infections in immunocompetent individuals are predominantly mild or unspecific, so that they often go unnoticed.

The infectious agents usually circulate among wild animals (reservoir hosts) and are transmitted among them mostly by hard ticks. Hard ticks are also considered to transmit these pathogens to other animal hosts such as livestock, domestic animals and humans. Prerequisites for transmission are exposure to infected ticks in their habitat, a sufficiently long attachment of the infected tick to the body for bloodsucking, and the absence of infection protection measures.

Further tick species and pathogens can also be introduced to Germany via wild animals, livestock, domestic animals or humans. For example, the repeated introduction via dogs of the brown dog tick *Rhipicephalus sanguineus* (vector of *Rickettsia (R.) conorii, R. massiliae,* and *Babesia vogeli*, among others) has been demonstrated since the 1970s, leading to its temporary establishment in buildings [56, 57]. Since the very warm years of 2018 and 2019, adult stages of the thermophilic species *Hyalomma (H.) marginatum* and *H. rufipes* have also been found in at least 12 of 16 German states [58–60]. They were probably introduced to Germany in their juvenile stages with migratory birds from Africa or southern Europe. Similar trends have been documented in several European countries, including Sweden, the United Kingdom, and the Netherlands [61–63]. *R. aeschlimanni*, a bacterium of the spotted fever group that is pathogenic to humans, was detected in about 30 to 40% of these ticks of the *H. marginatum* complex introduced to Germany. Crimean-Congo haemorrhagic fever virus (CCHFV) has not yet been detected in Germany [58, 59, 64]; however, *H. rufipes* infected with CCHFV was detected in a whinchat and a Western black-eared wheatear on the Italian island of Ventotene [65]. Increasing establishment of *H. marginatum* populations has been reported in southern Europe, Spain, and southern France, and isolated CCHFV detections in livestock, wild animals, and humans have been reported in southern Europe and Spain [66].

Whether previously non-native pathogens and tick species can establish in Germany and how the native host-tick-pathogen relationships already existing in Germany will develop depends on many factors, with climate change being a significant influence [67–69].

Ticks react directly to macro- and microclimatic factors in a species-specific manner, temperature and relative humidity being key factors. At higher temperatures and suitable humidity, for example, developmental processes are accelerated and thus the duration of moulting from one stage to the next or the duration of egg deposition is shortened [70–72]. Effects of climate change on native as well as medically relevant tick species with the potential of being introduced to Germany were investigated in more detail on behalf of the German Environment Agency [73, 74]. As a basis for modelling, georeferenced maps of Europe were produced for 17 tick species either native to Germany or with the potential for introduction, and the first tick atlas for Germany was published [75, 76] (current tick atlas published at [77]). *I. ricinus* is already widespread throughout Germany [74, 78] and in the course of climate change, higher tick abundances are possible in suitable biotopes, such as mixed oak-beech forests with undergrowth, sufficient hosts, and protective leaf litter. If, for example, under favourable climatic conditions, effective beech mast seeding occurs at shorter intervals, resulting in larger rodent populations [79, 80], more hosts are thus available for ticks such as *Ixodes* spp. and *Dermacentor* spp. to ingest blood and transmit pathogens. Temperature and humidity affect tick activity, developmental duration, diapause, overwintering, and survival rates. Individual active ticks have been observed at a soil temperature as low as 4°C [73].

Biotic and abiotic factors influence vector activity, reproduction, development, overwintering, and survival.

Distribution modelling for *D. reticulatus* and *D. marginatus* using MAXENT and BIOCLIM models (statistical habitat models), taking into account biological and geographic features and using data about landscape and bodies of water, indicates that further distribution of these tick species, especially *D. reticulatus*, is already possible in Germany at present [74, 81]. This was confirmed by more recent detections of these tick species in other regions [82, 83]. Habitat suitability modelling was also conducted for *H. marginatum* using MAXENT and BIOCLIM models [74, 84]. A projection for 2050 indicates that climatic conditions for *H. marginatum* will continue to improve in Germany [74]. Detection of ticks of the *H. marginatum* complex in Germany since 2018 confirms the introduction and suitability of conditions for the development into adults for these ticks, at least in warm and drier spring and summer periods. Modelling, especially when also considering host populations, e. g. modelling the potential spread of *H. marginatum* by migratory birds [85], supports the risk assessment and indicates where to look for these ticks in the context of systematic monitoring for early detection. In general, however, there are still large uncertainties in such models due to the multifactorial nature of the events and the dependence on model assumptions.

Rising temperatures, especially in the winter to summer months, hot spells and extreme weather, as well as changes in the water balance affecting relative humidity and air saturation deficit, influence the natural foci of infections together with their plant and animal habitats, including the hard ticks and the pathogens they harbour. Further research is needed in order to better understand the complex relationships and apply this knowledge to prevention strategies.

An ecological niche model showed that the distribution of locations with reported tick-borne encephalitis virus infection in Germany was associated with increased precipitation/temperature in summer and a decrease in frost days in winter.

The two most significant diseases transmitted by hard ticks are addressed below.

4.2 Tick-borne encephalitis

In Germany, the TBE virus is transmitted primarily by *I. ricinus* ticks, less frequently by other tick species (including *D. reticulatus*) or via infected raw milk (products). About 70 to 95% of infections are asymptomatic. Symptomatic diseases are sometimes mild, sometimes more severe with manifestations of the central nervous system (CNS) like meningitis, encephalitis, and myelitis. Up to 1% of those with CNS symptoms die [86]. Older persons generally have more severe symptoms than children. Nevertheless, severe forms of the disease can also occur in children.

TBE cases reported in Germany since 2001 according to IfSG show a pronounced seasonality, with most cases (98%) occurring between April and November. Annual case numbers vary widely between 195 (2012) and 712 cases (2020). From 2001 to 2016, a median of 276 cases were reported annually. From 2017 to 2022, the median annual number of cases was 505, an increase of over 200 cases. A statistically significant trend of an annual 2% increase in case numbers was observed from 2001 to 2018, as well as a seasonal shift such that infections occurred 0.69 days earlier each year [87, 88]. While *I. ricinus* is widespread throughout Germany and can also transmit the causative agent of Lyme borreliosis over a wide area, the TBE virus occurs endemically mainly in the south of Germany, in the form of small-scale natural foci. The number of at-risk rural and urban districts according to the RKI definition (five-year incidence>1:100,000) increased from 129 districts in 2007 to 175 districts in 2022 [86], with a significant expansion toward the north (Figure 2). The development in Saxony is remarkable: in 2014, the first district was declared a risk area; by 2022, 10 of 13 counties were risk areas. Moreover, about 3% of the reported cases occur outside the official risk areas [86].

The TBE virus circulates in nature between its vectors (ticks) and its natural hosts (small mammals such as the bank vole *Clethrionomys glareolus* or the yellow-necked mouse *Apodemus flavicollis*). Virus occurrence is thus determined by a complex interplay of climatic and ecological factors, which can affect the transmission cycle in different ways. They may act synergistically on both biological systems (vector and host), or antagonistically on one partner in the transmission system at a time, or on both systems. This complex interaction complicates predictions or modelling of the future evolution of TBE.

Warmer temperatures, especially mild winters and warm springs, are beneficial for tick activity and survival. If the temperature is too high in hot and dry summers, the ticks retreat into protective vegetation layers [89]. Our own studies show that especially the number of nymphs (juvenile stage) is significantly increased in spring after mild winters, i. e. more tick larvae and/or nymphs survive. Overall, however, adult tick numbers do not appear to increase. Dry spells in subsequent months potentially result in increased mortality of adults or nymphs that do not develop into adults. For effects of climate change on rodent populations, such as the bank vole, findings are summarised below (Section 5 Hantaviruses). There are no analyses to date on direct effects on small mammals infected with TBE virus and thus indirectly on the

Figure 2
Development of tick-borne encephalitis risk areas, 2007–2022
Source: Robert Koch Institute

transmission cycle of TBE virus. The influence of climatic factors on virus replication has also not been elucidated. However, there is evidence that certain TBE virus strains can adapt to different environmental temperatures within the tick [90]. An ecological niche model shows that the spread of TBE virus infection locations in Germany is significantly more frequent where precipitation and temperature are high in summer and few frost days occur in winter [91]. Given the foreseeable climatic changes, the habitat of *I. ricinus* may expand, especially in northern and eastern Europe, according to one modelling study [92]. Spread to higher altitudes has also been reported in the Czech Republic and elsewhere [93]. First TBE cases are regularly reported from countries previously considered TBE-free, e.g. the United Kingdom or the Netherlands in 2019 [94].

In addition to these abiotic factors, human behaviour also plays a role in infection risk. The record high of 712 TBE cases reported in 2020 was related not only to high tick occurrence but also to the fact that people went for more frequent walks during the COVID-19 pandemic [95]. Good conditions for mushroom picking can also lead to increased TBE virus infections in the fall. Warm periods can generally lead to increased time spent in nature and, if tick habitats are involved, to increased tick exposure and thus increased risk of infection.

Since there is no therapy to treat TBE, prevention is of great importance. Protective measures against tick bites, e.g. wearing long and light-coloured clothing, leaving no gaps between trousers and socks, and searching for attached ticks after each outdoor activity, can significantly reduce the risk of contracting the disease. In addition, TBE virus vaccination can effectively prevent infections [96]. In the majority (99%) of annual reported cases in Germany, people are unvaccinated or insufficiently vaccinated. Even in risk areas, only about 20% of the population has full

Prevention, especially vector control and exposure prevention, is of great importance for reducing the risk of infection with vector- and rodent-borne pathogens.

vaccination protection [86]. This means that there is great potential for preventing the majority of TBE cases by increasing vaccination rates.

4.3 Lyme borreliosis

Lyme borreliosis (or Lyme disease) is by far the most common vector-borne infectious disease in Germany.

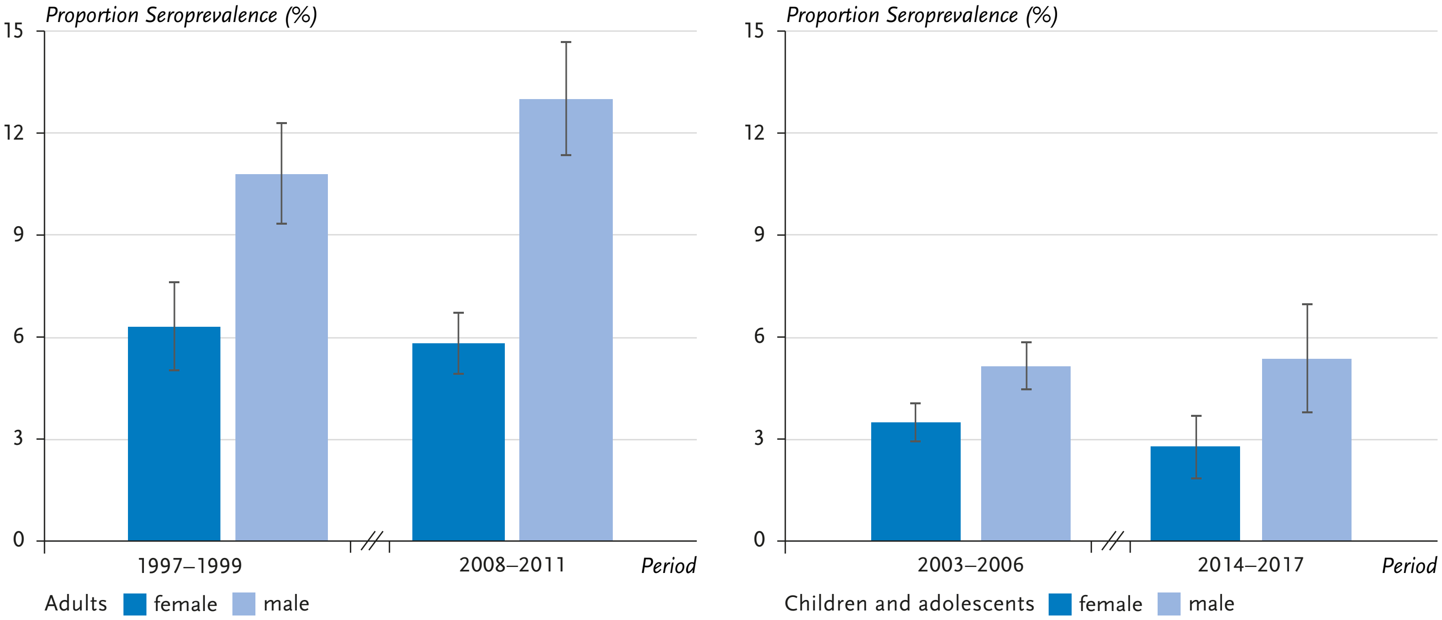
The bacteria *Borrelia (B.) burgdorferi* sensu lato (s.l.) transmitted by ticks (in central Europe mainly *I. ricinus)* are the causative agents of Lyme borreliosis, which can be accompanied by clinical manifestations of the skin (erythema migrans, acrodermatitis chronica athrophicans), nervous tissue (neuroborreliosis), joints (Lyme arthritis) and heart (Lyme carditis). Neuroborreliosis and Lyme carditis are sometimes associated with severe courses of disease. Lyme borreliosis occurs in all age groups and occurs, associated with the spread of its vectors, predominantly between the 40th and 60th parallel north, an area in which Germany and large parts of Europe are located.

Climate change may influence *B. burgdorferi* s.l. infections and the incidence of Lyme borreliosis within this area in a complex interplay of factors. It results in mild and wet winters and warmer springs in some regions. This extends the period of tick activity and density and increases the frequency of contact between humans and ticks, which leads to higher Lyme disease incidences. On the other hand, hot, dry summers are unsuitable for *I. ricinus* and may result in fewer infections. In addition, changing outdoor behaviours of people (e.g. spending time outdoors more frequently and earlier in the season) could alter the frequency of contact with ticks, leading to more frequent infections [97].

In Germany, representative surveys of *B. burgdorferi* seroprevalence in children and adolescents as well as in adults are regularly conducted by the RKI and the National Reference Centre for *Borrelia* (Figure 3). During the periods observed, there was a slight increase in men (18–79 years) and a slight decrease in girls (3–17 years) [98, 99]. However, a significant increase in the seroprevalence of *B. burgdorferi*-specific antibodies in the overall population was not observed. Thus, a change in the risk of infection by 2017 could not be confirmed in the serosurveys so far. This could be due to the fact that influences with opposite effects (increasing temperatures and greater drought) have balanced each other out or had different regional effects, making them undetectable by nationwide surveys. Furthermore, the previous study periods of about ten years may have been too short to detect long-term trends.

Lyme borreliosis is a notifiable disease in 9 of 16 German federal states [100, 101]. The temporal occurrence of reported cases shows a distinct seasonal pattern. Onset of the disease between June and August was reported in 57% of cases, with seasonality varying by clinical manifestation: cases of erythema migrans peak in July (22%), neuroborreliosis cases in August (20%), and Lyme arthritis cases are more evenly distributed throughout the year. The incidence of Lyme borreliosis is higher in months with higher temperatures. This seasonal distribution varies slightly from year to year, but it has remained relatively constant across federal states to date. Relevant changes in the seasonal pattern cannot be confirmed so far. This could be because climate change has little or no effect on seasonal differences in Lyme disease incidence. Alternatively, the influence of climate change on seasonality could be undetectable in

Figure 3
Representative estimates of *Borrelia burgdorferi* seroprevalence in adults (18–79 years) and children and adolescents (3–17 years) in Germany, 1997–2017
Source: Own representation after Woudenberg et al. [98].



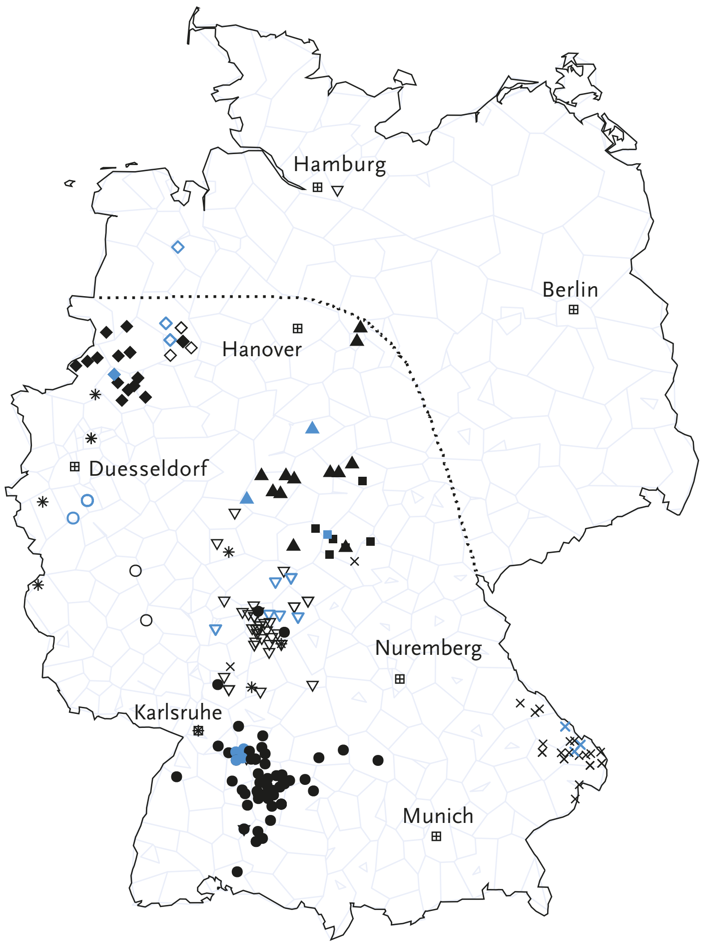
large-scale reporting data and effects may only be detectable on a smaller scale or be masked by artefacts in the reporting data.

Internationally, there are publications and reports from some regions that the distribution and incidence of Lyme borreliosis has increased in recent years in connection with warming (and thus more temperate winters and warm, humid summers), for example in the Midwest of the USA and in Canada [102]. Lyme borreliosis incidences have increased significantly in certain regions of Canada since surveillance began in 2009 [103]. This is primarily caused by a greater spread of the vector *I. scapularis*, mostly due to climate change. There has also been an increased spread of Lyme borreliosis in certain areas of northern Europe (e.g. Scotland) [104].

Modelling in the United States showed that in certain geographic areas (north-east), as temperatures continue to rise (according to climate scenarios), the incidence of Lyme borreliosis is likely to increase significantly in the coming decades [105]. However, these modelling efforts are subject to considerable uncertainty, and an increase in incidence could not be projected for all geographic regions considered. Another analysis in the United States found a significant association between temperature and incidence of Lyme borreliosis [106]. Assuming a 2°C increase in mean annual temperature over the next few decades, this study predicted an increase in cases of Lyme borreliosis of more than 20% in the United States.

A study from Austria evaluated the temporal and geographic trends of Lyme borreliosis and TBE for the period

Figure 4
Distribution of Puumala orthohantavirus sequences in Germany. The symbols correspond to those in Figure 6 and show infections from known endemic areas in Germany. Multiple sequences from the same location are shown only once.
Sequences originating from humans are depicted in black, those from bank voles in blue. The dotted line represents the hypothetical distribution boundary of PUUV-positive bank voles.
Source: Own representation after Drewes et al. [108] and Weiss et al. [114 (CC BY 4.0)]



PUUV=Puumala orthohantavirus

from 2005 to 2018 [107]. The incidences of the two diseases and their annual fluctuations were not geographically concordant, although the pathogens share the same tick vector and rodent reservoirs. Small-scale factors, some of which are still unknown, such as vector and pathogen biology and behavioural patterns, appear to play a role.

Although the factors influencing the incidence of Lyme borreliosis are complex, it can generally be assumed that climatic factors such as milder winters and warmer, more humid spring to autumn periods can lead to an increase in the incidence of infection and disease in certain small-scale regions.

5. Hantaviruses

Rodents act as important reservoir hosts and vectors of various zoonotic pathogens: bacteria, viruses and protozoa, i.e. eukaryotic unicellular organisms. There are also a number of viruses that exist in rodents but are not thought to be transmitted to humans and are considered rodent-specific. In this section, hantaviruses will be discussed as the epidemiologically most important rodent-borne group of pathogens, since a significant increase in knowledge about the ecological background of the hantavirus disease has been recorded in recent years. At least nine different hantaviruses occur in Germany; most human disease cases are caused by the Puumala orthohantavirus (PUUV). Although the reservoir host of PUUV, the bank vole (*Clethrionomys glareolus*), occurs throughout Germany, PUUV infections have only been detected in bank voles in the southern, western, and north-western parts of Germany. Extensive studies have led to the postulation of a northern and eastern distribution boundary of PUUV in the bank vole (Figure 4) [108]. In contrast, Dobrava-Belgrade orthohantavirus (DOBV), genotype Kurkino, occurs exclusively in the eastern part of Germany. This distribution is caused by the occurrence of the reservoir, the striped field mouse (*Apodemus agrarius*), which is restricted to eastern

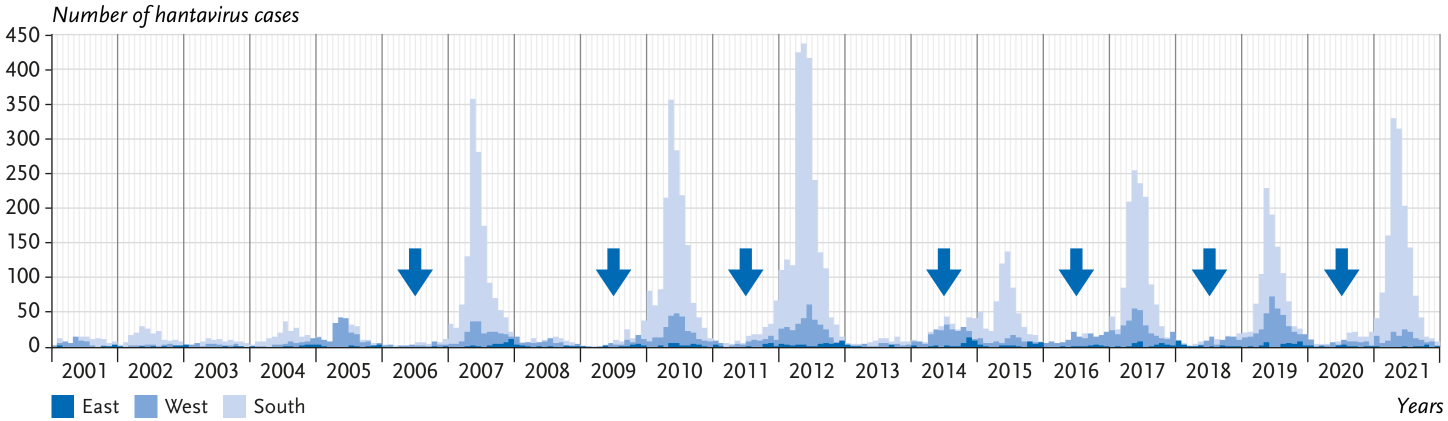
Germany. Infections of the yellow-necked mouse (*A. flavicollis*), which occurs throughout Germany, were found only in the range of the striped field mouse. Although DOBV has also been molecularly detected in the yellow-necked mouse and a strain of DOBV has been isolated, it is unclear to what extent the yellow-necked mouse can transmit the virus to humans [109, 110]. Tula orthohantavirus (TULV) is found throughout Germany in the common vole (*Microtus arvalis*), but has rarely been associated with human infection and disease [111, 112]. Seoul orthohantavirus (SEOV) is endemic in rat populations in parts of Asia and has been repeatedly detected in domestic rats in Europe and the United States; in Germany, isolated infections have occurred in connection with foreign travel or after contact with pet rats [113]. In addition, five other hantaviruses have been described in Germany whose human pathogenicity has not yet been clarified.

Hantavirus disease in humans is a classical zoonosis. Infection occurs by inhalation of dust contaminated with saliva, faeces, or urine of infected animals, by contact of injured skin with contaminated materials, or rarely through bites. Infection through ingestion of contaminated food is also possible. A large proportion of hantavirus infections are asymptomatic or present with non-specific symptoms, so that diagnostic clarification is often not initiated and significant underreporting can be assumed. Symptomatic infections with the virus species that are relevant to humans in Germany (PUUV, DOBV Kurkino) usually present as a flu-like illness with fever, colicky, often unilateral flank pain, nausea and diarrhoea, headache and neck stiffness, visual disturbances (myopia, photophobia), and conjunctival haemorrhages [115]. In Germany, symptomatic disease mainly affects adults aged 20 to 60 years and is extremely rare in children. Men are significantly overrepresented in all age groups [116]. It is likely that age and sex significantly influence susceptibility to infection as well as disease severity. Exposure factors seem to play a minor role at most. Symptomatic hantavirus infections with laboratory evidence have been notifiable according to IfSG since 2001. Data of the reported cases are transmitted anonymously and electronically from the health offices to the respective state health office and from there to the RKI.

The epidemiology of hantavirus disease in humans is characterised by cyclic PUUV outbreaks occurring approximately every two to three years, mainly in the south, west and north-west of Germany [116]. DOBV Kurkino, which occurs in the north and east of Germany, only produces a small number of sporadic cases of disease and will not be discussed in detail in this article focusing on climate change.

With a mean annual incidence of 2.3:100,000 inhabitants in Germany, the six largest outbreak years, 2007, 2010, 2012, 2017, 2019, and 2021, contributed a large proportion of the total cases reported in Germany between 2001 and 2021 (n=11,464 of 15,823; 72.4%). In the remaining 15 years, the mean annual incidence was much lower at 0.35:100,000 inhabitants (Figure 5). The majority of cases (n=10,988 of 15,823; 69.4%) were reported in Bavaria and Baden-Württemberg, where known PUUV endemic areas are located (e. g. Swabian Alps, Lower Franconia, Bavarian Forest). The remaining federal states contribute relatively few cases, although endemic areas located there (e. g. the Osnabrück region or western Thuringia) also report locally high incidences in outbreak years. A detailed molecular analysis of PUUV outbreaks up to 2018, as well as current studies of

Figure 5
Reported hantavirus cases by region, year and month of disease onset in Germany, 2001–2021 (n=14.786 cases with known date).
Arrows indicate beech mast years (>40% of beech trees showing medium or high fructification) in Baden-Württemberg [117].
Source: Own representation



South=Baden-Württemberg, Bavaria, Hesse, Rhineland-Palatinate, Saarland, Thuringia; East=Brandenburg, Berlin, Mecklenburg-Western Pomerania, Saxony, Saxony-Anhalt; West=Bremen, Hamburg, Lower Saxony, North Rhine-Westphalia, Schleswig-Holstein

bank voles at the postulated PUUV distribution boundary, show a separate evolutionary development of viruses specific to each endemic area over long periods of time (Figure 6). This suggests that the spatial extent of the different endemic areas is stable over time.

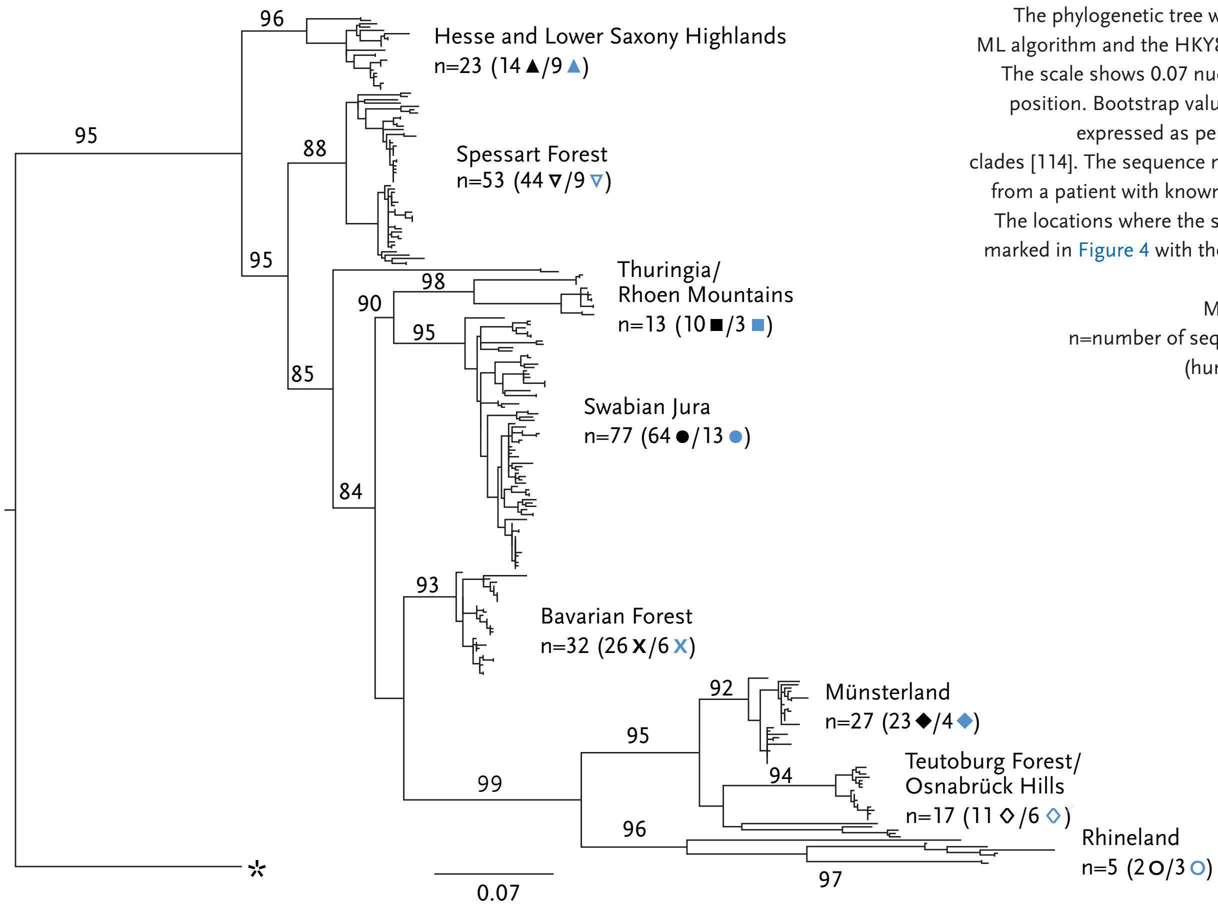
Hantavirus disease shows marked seasonality, with the case numbers peaking in spring or early summer (Figure 5). A gradual increase in case numbers through fall and winter seems to indicate an upcoming outbreak year. Nevertheless, hantavirus disease must also be considered outside this peak season; for example, a cluster of cases was reported in a small company in Lower Saxony in December 2017 [118].

The incidence of PUUV disease in the population is closely linked to the presence and abundance of bank voles [119]. A high population density of bank voles increases the transmission rate within the bank vole population, resulting in higher PUUV prevalence there [120, 121]. An increase in the population of infected reservoir animals increases the amount of virus-containing excreta in the environment and the likelihood that humans will come into contact with them. This, in turn, may lead to an increased rate of human infection. Therefore, when considering the influence of climate change on the future incidence of PUUV disease, it is critical to forecast future trends in bank vole populations. This in turn depends strongly on the future development of forests, especially beech forests.

The abundance of bank voles is subject to cyclic fluctuations. Mass reproductions are triggered by mast years, i.e. years in which there is above-average fructification of the bank voles' food plants, mainly beech (*Fagus sylvatica*). Mass reproductions of bank voles regularly occur in years following mast years [119, 121].

The frequency with which mast years occur is climate-dependent. There is evidence that climate change has increased the frequency of mast years over the last hundred years [122, 123]. Consequently, the frequency of years with

Figure 6
Phylogenetic analysis of Puumala orthohantavirus S-segment sequence based on a 504 nucleotide alignment of 258 sequences published in GenBank
Source: Own representation after Drewes et al. [108] and Weiss et al. [114 (CC BY 4.0)]



The phylogenetic tree was constructed using the ML algorithm and the HKY85 +R substitution model. The scale shows 0.07 nucleotide substitutions per position. Bootstrap values (1000 iterations) were expressed as percentages for the relevant clades [114]. The sequence marked with an asterisk is from a patient with known rodent exposure abroad. The locations where the sequences were found are marked in Figure 4 with the corresponding symbols.

ML = Maximum Likelihood;
n = number of sequences within each clade (human origin/rodent origin)

mass reproductions of bank voles has also increased, such that mast years followed by mass reproductions of bank voles now occur every two to three years (Figure 5). However, the increase in frequency of mast years is limited by the fact that a tree cannot produce a full mast in two consecutive years because above-average fruit production is associated with high physiological stress, which is evident through significantly reduced tree thickness growth in mast years [124]. However, it is possible that climate change could break the spatial synchronicity of mast events. This would result in mass fructification in beech trees occurring in a spatially heterogeneous manner [125, 126]. Such asynchronous mast events and their effect on bank vole populations have already been observed, suggesting that future outbreaks could be more localised rather than supra-regional or nationwide [127]. Evidence also suggests that

The potential impact of climate change on human disease caused by Puumala orthohantavirus has not been conclusively determined.

warm, wet winters favour transmission of PUUV within bank vole populations, regardless of their size and density, at least in northern Europe. Thus, climate may also have a direct influence on PUUV survival in the environment [128]. In Germany, however, climate change is more likely to affect forests by increasing drought. Based on observations of the drought years 2018 to 2020, it can be predicted that more than 30% of forested areas with beech as the main tree species and an important food source for bank voles are at risk [129]. In drought years, beech trees prematurely shed stunted beechnuts, despite having previously fruited well, providing only scarce food for bank voles [130]. Furthermore, it is likely that extreme weather events such as storms or heavy rainfall, in addition to forest fires as a consequence of drought, will have an impact on the occurrence of bank voles and PUUV. What consequences all these phenomena will have on bank vole populations and thus ultimately on the incidence of PUUV disease is not yet clear and must be the subject of further investigations. However, due to the above-mentioned natural limitation of the frequency of mast years as well as the expected negative climate effects on the growth and distribution of beech, a strong increase in the incidence of hantavirus disease in Germany in connection with the effects of climate change is not currently expected.

6. Recommendations

6.1 General recommendations

The following generally applicable recommendations can be made to protect the population from vector- and rodent-borne diseases in Germany:

(1) Strengthen science and research capacity on climate change and health to provide a more accurate assessment of the impact of climatic changes on vector- and rodent-borne infectious diseases

(2) Maintain or strengthen interagency One Health-based collaboration in the health, environmental, and animal health sectors to ensure more effective interdisciplinary collaboration for infection prevention

(3) Expand monitoring of vector- and rodent-borne infectious agents in humans and animals

(4) Targeted information campaigns on infection risks and protective measures for the population

(5) Development of communication strategies for the medical profession

(6) Continuing education (a) of professionals related to behavioural prevention and health promotion in human and veterinary medical practices or facilities of the Public Health Service (Öffentlicher Gesundheitsdienst, ÖGD), (b) of employees in pest control companies, (c) of professionals working outdoors with an increased risk of infection, e.g. in forestry, and (d) of occupational health and safety specialists for these occupational groups

6.2 Targeted recommendations

The generally applicable recommendations are supplemented by the following targeted recommendations for Germany:

Infectious diseases associated with mosquitoes

(1) Promote the development of local response plans for WNV as well as the emergence of new vector-competent mosquito species (e.g. *Ae. albopictus*)

Further research is needed to better understand the impact of climate change on zoonotic pathogens, their reservoirs and vectors.

(2) Public information campaigns to prevent mosquito reproduction sites and the spread of new mosquito species

(3) Consideration of prevention measures, such as breeding site prevention or elimination, when planning of climate-resilient cities

(4) Sensitisation of the ÖGD to reported cases (Info box 1)

Info box 1: Recommendations for the Public Health Service (ÖGD) with regard to DENV, CHIKV and ZIKV infections

Local health authorities should seasonally point out the risk of further transmission in reported cases of suspected viraemic DENV, CHIKV and ZIKV infections in areas with *Ae. albopictus* and be alert for non-travel-associated secondary cases [131]. Physicians in relevant areas should also seasonally consider these pathogens, which are not endemic in Germany, in the event of clusters of illnesses with fever and/or skin rash and, if necessary, initiate appropriate diagnostics.

Info box 2: Recommendations for the ÖGD with regard to tick-borne diseases

Public health authorities should continue to provide preventive education about avoiding tick bites and removing ticks immediately. In addition, the public should also be informed about clinical manifestations, such as erythema migrans, in order to receive early medical attention and ensure early diagnosis and treatment, which can prevent more severe disease progression. A focus of these communication efforts could be on specific groups at increased risk of tick bites, e.g. people working in the forest or in public facilities in or near the forest (e.g. forest kindergartens, children's and youth camps), members of Scouting associations, geocachers, people who collect mushrooms, or beekeepers.

Infectious diseases associated with hard ticks

(1) Assurance of correct tick identification as a basis for correct recognition of causal relationships

(2) Contact and exchange between scientists carrying out tick- and rodent-borne pathogen studies

(3) Development of effective and sustainable products, procedures, methods, and strategies to protect against tick infestation and pathogen transmission (including tick vaccine development, biological tick control, tick traps, effective repellents)

(4) Promote and conduct further representative surveys on the prevalence of *B. burgdorferi*-specific antibodies to detect a possible increase, which may be partly due to climatic factors

(5) Promote and conduct studies on the incidence and trends of erythema migrans in selected geographic regions

(6) Prevention measures and information by the ÖGD (Info box 2)

(7) Education of the public and the medical community about Lyme borreliosis (Info box 3)

Hantaviruses

(1) Increased dissemination of information on hantavirus infections to populations in affected areas, e.g. using the RKI fact sheet [132]

(2) Seasonal and targeted communication on the risk of hantavirus infections (Info box 4)

(3) Continuous surveillance of hantavirus infections in humans and monitoring of trends in the animal reservoir

(4) Networking of studies on various rodent- and vector-borne zoonotic pathogens

(5) Further development of hantavirus forecasting models and fine-resolution risk maps

(6) Promote and conduct studies on the synchronicity or increasing asynchronicity of bank vole mass reproductions

Info box 3: Required communication strategies for Lyme borreliosis

Misconceptions about the symptoms and diagnostic frequency of Lyme borreliosis exist in parts of the population, which have been spread for some time via social networks and blogging services. Individuals are sometimes incorrectly diagnosed with Lyme borreliosis and are subjected to prolonged suffering until they receive a correct diagnosis and therapy. Consequences include unnecessary burdens on the health care system, confused and dissatisfied patients, and the initiation of ineffective therapies such as antibiotic treatments. Communication strategies should educate the population about the disease, correct diagnostic options, and possible differential diagnoses of Lyme borreliosis.

Info box 4: Communication on the risk of hantavirus infections to the population

Education of the population on the risk of hantavirus infections and corresponding prevention measures should be carried out seasonally using selected communication strategies. In addition to direct information aimed at the general population, relevant community and interest groups should also be involved to provide targeted information to particularly exposed groups of people like forest workers and those working in pest control. While for PUUV in its distribution area predictions are possible, this is not yet the case for DOBV due to its sporadic occurrence. Therefore, general information should be provided in the distribution area of this virus (eastern part of Germany). The first detection of hantavirus infections caused by pet rats (Seoul orthohantavirus) has made clear that keepers and sellers of pet rats have to be informed about this risk; mandatory testing of pet rats for this and other pathogens would be desirable.

7. Conclusion

Higher temperatures, changing precipitation patterns, and human behaviour may influence the epidemiology of vector- and rodent-borne infectious diseases in Germany. The effects of climatic changes on the spread of vector- and rodent-borne infectious diseases need to be further studied in detail and considered in climate adaptation measures.

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Conflicts of interest

Sandra Beermann declares that she has been seconded to the Federal Ministry of Health since June 2022. The other authors declare that there are no conflicts of interest.

Authors' contributions

All authors have made comparable contributions and are listed in alphabetical order.
Coordination and editing of the overall manuscript, preparation of the introduction and abstract: Beermann S, Wilking H
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Section 4 – Infectious diseases associated with hard ticks: Dobler G, Habedank B, Hagedorn P, Nygren TM, Stark K, Wilking H
Section 5 – Hantaviruses: Faber M, Schmolz E, Ulrich RG, Weiss S

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References

1. Bruce-Chwatt L, de Zulueta J (1980) The rise and fall of malaria in Europe: A historico-epidemiological study. Oxford University Press, Oxford
2. Kuhlisch C (2022) Discovery of *Aedes (Ochlerotatus) pionips* Dyar, 1919 (Diptera, Culicidae) in Germany. Check List 18:897–906
3. Pernat N, Kampen H, Jeschke JM et al. (2021) Citizen science versus professional data collection: Comparison of approaches to mosquito monitoring in Germany. J Appl Ecol 58:214–223
4. Walther D, Kampen H (2017) The citizen science project 'Mueckenatlas' helps monitor the distribution and spread of invasive mosquito species in Germany. J Med Entomol 54(6):1790–1794
5. Reisen WK (1989) Estimation of vectorial capacity: Introduction/relationship to disease transmission by malaria and arbovirus vectors. Bull Soc Vector Ecol 14(2):39–40, 67–70
6. Kampen H, Kuhlisch C, Frohlich A et al. (2016) Occurrence and spread of the invasive Asian bush mosquito *Aedes japonicus japonicus* (Diptera: Culicidae) in West and North Germany since detection in 2012 and 2013, respectively. PLoS One 11(12):e0167948
7. Ratte HT (1984) Temperature and insect development. In: Hoffmann KH (Ed) Environmental physiology and biochemistry of insects. Springer, Berlin; Heidelberg, P. 33–66
8. Mellor PS, Leake CJ (2000) Climatic and geographic influences on arboviral infections and vectors. Rev Sci Tech 19(1):41–54
9. Kamiya T, Greischar MA, Wadhawan K et al. (2019) Temperature-dependent variation in the extrinsic incubation period elevates the risk of vector-borne disease emergence. Epidemics 30:100382
10. Jansen S, Cadar D, Lühken R et al. (2021) Vector competence of the invasive mosquito species *Aedes koreicus* for arboviruses and interference with a novel insect specific virus. Viruses 13(12):2507
11. Jansen S, Heitmann A, Lühken R et al. (2018) Experimental transmission of Zika virus by *Aedes japonicus japonicus* from southwestern Germany. Emerg Microbes Infect 7(1):192
12. Jansen S, Heitmann A, Lühken R et al. (2019) *Culex torrentium*: A potent vector for the transmission of West Nile virus in Central Europe. Viruses 11(6):492
13. Ziegler U, Lühken R, Keller M et al. (2019) West Nile virus epizootic in Germany, 2018. Antiviral Res 162:39–43
14. Kampen H, Holicki CM, Ziegler U et al. (2020) West Nile virus mosquito vectors (Diptera: Culicidae) in Germany. Viruses 12(5):493

15. Komar N, Langevin S, Hinten S et al. (2003) Experimental infection of North American birds with the New York 1999 strain of West Nile virus. Emerg Infect Dis 9(3):311–322

16. Hubálek Z, Halouzka J (1999) West Nile fever – A reemerging mosquito-borne viral disease in Europe. Emerg Infect Dis 5(5):643–650

17. Young JJ, Haussig JM, Aberle SW et al. (2021) Epidemiology of human West Nile virus infections in the European Union and European Union enlargement countries, 2010 to 2018. Euro Surveill 26(19):2001095

18. Brugman VA, Hernandez-Triana LM, Medlock JM et al. (2018) The role of *Culex pipiens* L. (Diptera: Culicidae) in virus transmission in Europe. Int J Env Res Public Health 15(2):389

19. Kampen H, Tews BA, Werner D (2021) First evidence of West Nile virus overwintering in mosquitoes in Germany. Viruses 13(12):2463

20. Werner D, Kowalczyk S, Kampen H (2020) Nine years of mosquito monitoring in Germany, 2011–2019, with an updated inventory of German culicid species. Parasitol Res 119(9):2765–2774

21. Lowe S, Browne M, Boudjelas S et al. (2000) 100 of the world's worst invasive alien species: A selection from the Global Invasive Species Database. The Invasive Species Specialist Group, a specialist group of the Species Survival Commission of the World Conservation Union, New Zealand. https://portals.iucn.org/library/sites/library/files/documents/2000-126.pdf (As at 20.12.2022)

22. Cancrini G, Di Frangipane Regalbono A, Ricci I et al. (2003) *Aedes albopictus* is a natural vector of *Dirofilaria immitis* in Italy. Vet Parasitol 118(3–4):195–202

23. Paupy C, Delatte H, Bagny L et al. (2009) *Aedes albopictus*, an arbovirus vector: From the darkness to the light. Microbes Infect 11(14–15):1177–1185

24. Rezza G (2014) Dengue and chikungunya: Long-distance spread and outbreaks in naive areas. Pathog Glob Health 108(8):349–355

25. Becker N, Geier M, Balczun C et al. (2013) Repeated introduction of *Aedes albopictus* into Germany, July to October 2012. Parasitol Res 112(4):1787–1790

26. Reiter P (1998) *Aedes albopictus* and the world trade in used tires, 1988–1995: The shape of things to come? J Am Mosq Control Assoc 14(1):83–94

27. Walther D, Scheuch DE, Kampen H (2017) The invasive Asian tiger mosquito *Aedes albopictus* (Diptera: Culicidae) in Germany: Local reproduction and overwintering. Acta Trop 166:186–192

28. Nationale Expertenkommission "Stechmücken als Überträger von Krankheitserregern" am Friedrich-Loeffler-Institut (2022) Vorkommen der Asiatischen Tigermücke *Aedes albopictus* in Deutschland. https://www.fli.de/de/kommissionen/nationale-expertenkommission-stechmuecken-als-uebertraeger-von-krankheitserregern (As at 15.12.2022)

29. Becker N, Schön S, Klein AM et al. (2017) First mass development of *Aedes albopictus* (Diptera: Culicidae) – Its surveillance and control in Germany. Parasitol Res 116(3):847–858

30. Kobayashi M, Nihei N, Kurihara T (2002) Analysis of northern distribution of *Aedes albopictus* (Diptera: Culicidae) in Japan by geographical information system. Journal of Med Entomol 39(1):4–11

31. Waldock J, Chandra NL, Lelieveld J et al. (2013) The role of environmental variables on *Aedes albopictus* biology and chikungunya epidemiology. Pathog Glob Health 107(5):224–241

32. Tippelt L, Werner D, Kampen H (2019) Tolerance of three *Aedes albopictus* strains (Diptera: Culicidae) from different geographical origins towards winter temperatures under field conditions in northern Germany. PLoS One 14(7):e0219553

33. Tippelt L, Werner D, Kampen H (2020) Low temperature tolerance of three *Aedes albopictus* strains (Diptera: Culicidae) under constant and fluctuating temperature scenarios. Parasit Vectors 13(1):587

34. Fischer D, Thomas SM, Neteler M et al. (2014) Climatic suitability of *Aedes albopictus* in Europe referring to climate change projections: Comparison of mechanistic and correlative niche modelling approaches. Euro Surveill 19(6):20696

35. Thomas SM, Tjaden NB, Frank C et al. (2018) Areas with high hazard potential for autochthonous transmission of *Aedes albopictus*-associated arboviruses in Germany. Int J Env Res Public Health 15(6):1270

36. Cunze S, Kochmann J, Koch LK et al. (2016) *Aedes albopictus* and its environmental limits in Europe. PLoS One 11(9):e0162116

37. Kampen H, Walther D (2018) Vector potential of mosquito species occurring in central Europe: Mosquito-borne diseases. In: Benelli G, Mehlhorn H (Eds) Parasitology Research Monographs, Vol 10, Springer, Cham, P. 41–68
38. Koban MB, Kampen H, Scheuch DE et al. (2019) The Asian bush mosquito *Aedes japonicus japonicus* (Diptera: Culicidae) in Europe, 17 years after its first detection, with a focus on monitoring methods. Parasit Vectors 12(1):109
39. Pfitzner WP, Lehner A, Hoffmann D et al. (2018) First record and morphological characterization of an established population of *Aedes (Hulecoeteomyia) koreicus* (Diptera: Culicidae) in Germany. Parasit Vectors 11(1):662
40. Tsai TF, Popovici F, Cernescu C et al. (1998) West Nile encephalitis epidemic in southeastern Romania. Lancet 352(9130):767–771
41. May FJ, Davis CT, Tesh RB et al. (2011) Phylogeography of West Nile virus: From the cradle of evolution in Africa to Eurasia, Australia, and the Americas. J Virol 85(6):2964–2974
42. European Centre for Disease Prevention and Control (2019) West Nile virus infection. In: ECDC (Eds) Annual epidemiological report for 2018. ECDC, Stockholm. https://www.ecdc.europa.eu/en/publications-data/west-nile-virus-infection-annual-epidemiological-report-2018 (As at 20.12.2022)
43. Frank C, Schmidt-Chanasit J, Ziegler U (2022) West Nile virus in Germany: An emerging infection and its relevance for transfusion safety. Transfus Med Hemother 49:192–203
44. Petersen LR, Brault AC, Nasci RS (2013) West Nile virus: Review of the literature. JAMA 310(3):308–315
45. Offergeld R, Schmidt-Chanasit J, Frank C (2022) West Nil-Virus in Deutschland – Relevanz für die Transfusionssicherheit. Hämotherapie 38:23–33
46. Lorenz C, Azevedo TSd, Chiaravalloti-Neto F (2022) Impact of climate change on West Nile virus distribution in South America. Tran R Soc Trop Med Hyg 116(11):1043–1053
47. Caputo B, Russo G, Manica M et al. (2020) A comparative analysis of the 2007 and 2017 Italian chikungunya outbreaks and implication for public health response. PLoS Negl Trop Dis 14(6):e0008159
48. Giron S, Franke F, Decoppet A et al. (2019) Vector-borne transmission of Zika virus in Europe, southern France, August 2019. Euro Surveill 24(45):1900655
49. Schmidt-Chanasit J, Haditsch M, Schoneberg I et al. (2010) Dengue virus infection in a traveller returning from Croatia to Germany. Euro Surveill 15(40):19677
50. Heitmann A, Jansen S, Lühken R et al. (2018) Experimental risk assessment for chikungunya virus transmission based on vector competence, distribution and temperature suitability in Europe, 2018. Euro Surveill 23(29):1800033
51. Heitmann A, Jansen S, Lühken R et al. (2017) Experimental transmission of Zika virus by mosquitoes from central Europe. Euro Surveill 22(2):30437
52. Mercier A, Obadia T, Carraretto D et al. (2022) Impact of temperature on dengue and chikungunya transmission by the mosquito *Aedes albopictus*. Sci Rep 12(1):6973
53. Cochet A, Calba C, Jourdain F et al. (2022) Autochthonous dengue in mainland France, 2022: Geographical extension and incidence increase. Euro Surveill 27(44):2200818
54. Petney T, Moser E, Littwin N et al. (2015) Additions to the 'Annotated Checklist of the Ticks of Germany': *Ixodes acuminatus* and *Ixodes inopinatus*. Exp Appl Acarol 20:221–224
55. Petney T, Pfäffle M, Skuballa J (2012) An annotated checklist of the ticks (Acari: Ixodida) of Germany. Syst Appl Acarol 17:115–170
56. Fachet K, Lindau A, Mackenstedt U (2022) Ungebetenes Souvenir – der Hund als Transportmittel für *Rhipicephalus sanguineus* s.l. In: 6. Süddeutscher Zeckenkongress 28. – 30. März 2022, Hohenheim, P. 39. https://zeckenkongress.de/wp-content/uploads/2022/03/tagungsband2.pdf (As at 20.12.2022)
57. Hoffmann G (1981) Die Braune Hundezecke (*Rhipicephalus sanguineus* L.) in Berlin (West). Epizootiologische Untersuchungen unter Einschaltung von Massenmedien. Bundesgesundheitsbl 24(3):41–50
58. Chitimia-Dobler L, Schaper S, Rieß R et al. (2019) Imported *Hyalomma* ticks in Germany in 2018. Parasit Vectors 12(1):134
59. Hagedorn D (2019) Fund von Zecken der Gattung *Hyalomma* in Deutschland. Epid Bull 7:70–71

60. Lindau A, Drehmann M, Springer A et al. (2022) *Hyalomma* in Deutschland - 3 Jahre Citizen Science. In: 6 Süddeutscher Zeckenkongress 28. – 30. März 2022, Hohenheim, P. 36. https://zeckenkongress.de/wp-content/uploads/2022/03/tagungsband2.pdf (As at 20.12.2022)
61. Grandi G, Chitimia-Dobler L, Choklikitumnuey P et al. (2020) First records of adult *Hyalomma marginatum* and *H. rufipes* ticks (Acari: Ixodidae) in Sweden. Ticks Tick Borne Dis 11(3):101403
62. Hansford KM, Carter D, Gillingham EL et al. (2019) *Hyalomma rufipes* on an untraveled horse: Is this the first evidence of *Hyalomma* nymphs successfully moulting in the United Kingdom? Ticks Tick Borne Dis 10(3):704–708
63. Uiterwijk M, Ibáñez-Justicia A, van de Vossenberg B et al. (2021) Imported *Hyalomma* ticks in the Netherlands 2018–2020. Parasit Vectors 14(1):244
64. Chitimia-Dobler L, Nava S, Bestehorn M et al. (2016) First detection of *Hyalomma rufipes* in Germany. Ticks Tick Borne Dis 7(6):1135–1138
65. Mancuso E, Toma L, Pascucci I et al. (2022) Direct and indirect role of migratory birds in spreading CCHFV and WNV: A multidisciplinary study on three stop-over islands in Italy. Pathogens 11(9):1056
66. Portillo A, Palomar AM, Santibáñez P et al. (2021) Epidemiological aspects of Crimean-Congo hemorrhagic fever in Western Europe: What about the future? Microorganisms 9(3):649
67. Gray JS, Dautel H, Estrada-Peña A et al. (2009) Effects of climate change on ticks and tick-borne diseases in Europe. Interdiscip Perspect Infect Dis 2009:593232
68. Medlock JM, Hansford KM, Bormane A et al. (2013) Driving forces for changes in geographical distribution of *Ixodes ricinus* ticks in Europe. Parasit Vectors 6(1):1
69. Kahlenborn W, Porst L, Voß M et al. (2021) Klimawirkungs- und Risikoanalyse für Deutschland 2021 (Kurzfassung). Umweltbundesamt (Eds) Climate Change 26/2021. https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/kwra2021_teilbericht_zusammenfassung_bf_211027_0.pdf (As at 18.01.2023)
70. Gothe R, Hamel HD (1973) Zur Ökologie eines deutschen Stammes von *Rhipicephalus sanguineus* (Latreille, 1806). Z Parasitenkd 41(2):157–172
71. Zahler M, Gothe R (1995) Effect of temperature and humidity on longevity of unfed adults and on oviposition of engorged females of *Dermacentor reticulatus* (Ixodidae). Appl Parasitol 36(3):200–211
72. Zahler M, Gothe R (1995) Effect of temperature and humidity on egg hatch, moulting and longevity of larvae and nymphs of *Dermacentor reticulatus* (Ixodidae). Appl Parasitol 36(1):53–65
73. Gethmann J, Hoffmann B, Kasbohm E et al. (2020) Research paper on abiotic factors and their influence on *Ixodes ricinus* activity – Observations over a two-year period at several tick collection sites in Germany. Parasitol Res 119(5):1455–1466
74. Kahl O, Dautel H, Mackenstedt U et al. (2016) Auswirkungen des Klimawandels auf das Vorkommen, die Aktivität und Verbreitung von als Überträger von Krankheitserregern bedeutenden Schildzecken. Fortführung von Vorhaben FKZ 3711 48 402. Forschungsbericht FB 002708 im Auftrag des Umweltbundesamtes, Umweltbundesamt
75. Rubel F, Brugger K, Monazahian M et al. (2014) The first German map of georeferenced ixodid tick locations. Parasit Vectors 7(1):477
76. Rubel F, Brugger K, Pfeffer M et al. (2016) Geographical distribution of *Dermacentor marginatus* and *Dermacentor reticulatus* in Europe. Ticks Tick Borne Dis 7(1):224–233
77. Rubel F, Brugger K, Chitimia-Dobler L et al. (2021) Atlas of ticks (Acari: Argasidae, Ixodidae) in Germany. Exp Appl Acarol 84(1):183–214
78. Brugger K, Boehnke D, Petney T et al. (2016) A density map of the tick-borne encephalitis and Lyme borreliosis vector *Ixodes ricinus* (Acari: Ixodidae) for Germany. J Med Entomol 53(6):1292–1302
79. Imholt C, Reil D, Eccard JA et al. (2015) Quantifying the past and future impact of climate on outbreak patterns of bank voles (*Myodes glareolus*). Pest Manag Sci 71(2):166–172
80. Reil D, Imholt C, Eccard JA et al. (2015) Beech fructification and bank vole population dynamics – Combined analyses of promoters of human Puumala virus infections in Germany. PLoS One 10(7):e0134124
81. Walter M, Brugger K, Rubel F (2016) The ecological niche of *Dermacentor marginatus* in Germany. Parasitol Res 115(6):2165–2174

82. Drehmann M, Springer A, Lindau A et al. (2020) The spatial distribution of *Dermacentor* ticks (Ixodidae) in Germany – Evidence of a continuing spread of *Dermacentor reticulatus*. Front Vet Sci 7:578220

83. Răileanu C, Tauchmann O, Silaghi C (2022) Sympatric occurrence of *Ixodes ricinus* with *Dermacentor reticulatus* and *Haemaphysalis concinna* and the associated tick-borne pathogens near the German Baltic coast. Parasit Vectors 15(1):65

84. Fernández-Ruiz N, Estrada-Peña A (2021) Towards new horizons: Climate trends in Europe increase the environmental suitability for permanent populations of *Hyalomma marginatum* (Ixodidae). Pathogens 10(2):95

85. Estrada-Peña A, D'Amico G, Fernández-Ruiz N (2021) Modelling the potential spread of *Hyalomma marginatum* ticks in Europe by migratory birds. Int J Parasitol 51(1):1–11

86. Robert Koch-Institut (2022) FSME: Risikogebiete in Deutschland (Stand Januar 2022). Epid Bull 9:3–21

87. Borde JP, Kaier K, Hehn P et al. (2019) Tick-borne encephalitis virus infections in Germany. Seasonality and in-year patterns. A retrospective analysis from 2001–2018. PLoS One 14(10):e0224044

88. Hellenbrand W, Kreusch T, Bohmer MM et al. (2019) Epidemiology of tick-borne encephalitis (TBE) in Germany, 2001–2018. Pathogens 8(2):42

89. Daniel M, Danielova V, Fialova A et al. (2018) Increased relative risk of tick-borne encephalitis in warmer weather. Front Cell Infect Microbiol 8:90

90. Elvang A, Melik W, Bertrand Y et al. (2011) Sequencing of a tick-borne encephalitis virus from *Ixodes ricinus* reveals a thermosensitive RNA switch significant for virus propagation in ectothermic arthropods. Vector Borne Zoonotic Dis 11(6):649–658

91. Friedsam AM, Brady OJ, Pilic A et al. (2022) Geo-spatial characteristics of 567 places of tick-borne encephalitis infection in southern Germany, 2018–2020. Microorganisms 10(3):643

92. Alkishe AA, Peterson AT, Samy AM (2017) Climate change influences on the potential geographic distribution of the disease vector tick *Ixodes ricinus*. PLoS One 12(12):e0189092

93. Daniel M, Danielová V, Kríz B et al. (2003) Shift of the tick *Ixodes ricinus* and tick-borne encephalitis to higher altitudes in central Europe. Eur J Clin Microbiol Infect Dis 22(5):327–328

94. Kreusch TM, Holding M, Hewson R et al. (2019) A probable case of tick-borne encephalitis (TBE) acquired in England, July 2019. Euro Surveill 24(47):1900679

95. Nygren TM, Pilic A, Böhmer MM et al. (2022) Tick-borne encephalitis risk increases with dog ownership, frequent walks, and gardening: A case-control study in Germany 2018–2020. Microorganisms 10(4):690

96. Nygren TM, Pilic A, Böhmer MM et al. (2022) Tick-borne encephalitis vaccine effectiveness and barriers to vaccination in Germany. Sci Rep 12(1):11706

97. Medlock JM, Leach SA (2015) Effect of climate change on vector-borne disease risk in the UK. Lancet Infect Dis 15(6):721–730

98. Woudenberg T, Böhm S, Böhmer M et al. (2020) Dynamics of *Borrelia burgdorferi*-specific antibodies: Seroconversion and seroreversion between two population-based, cross-sectional surveys among adults in Germany. Microorganisms 8(12):1859

99. Böhm S, Woudenberg T, Böhmer M et al. (eingereicht) Seroprevalence, seroconversion and seroreversion of *Borrelia burgdorferi* specific antibodies using two population-based studies in children and adolescents in Germany (KiGGS), 2003–2006 and 2014–2017

100. Enkelmann J, Böhmer M, Fingerle V et al. (2018) Incidence of notified Lyme borreliosis in Germany, 2013–2017. Sci Rep 8(1):14976

101. Wilking H, Stark K (2014) Trends in surveillance data of human Lyme borreliosis from six federal states in eastern Germany, 2009–2012. Ticks Tick Borne Dis 5(3):219–224

102. Semenza JC, Rocklöv J, Ebi KL (2022) Climate change and cascading risks from infectious disease. Infect Dis Ther 11(4):1371–1390

103. Ogden NH, Bouchard C, Badcock J et al. (2019) What is the real number of Lyme disease cases in Canada? BMC Public Health 19(1):849

104. Millins C, Leo W, MacInnes I et al. (2021) Emergence of Lyme disease on treeless islands, Scotland, United Kingdom. Emerg Infect Dis 27(2):538–546

105. Couper LI, MacDonald AJ, Mordecai EA (2021) Impact of prior and projected climate change on US Lyme disease incidence. Glob Chang Biol 27(4):738–754

106. Dumic I, Severnini E (2018) 'Ticking Bomb': The impact of climate change on the incidence of Lyme disease. Can J Infect Dis Med Microbiol 2018:5719081

107. Stiasny K, Santonja I, Holzmann H et al. (2021) The regional decline and rise of tick-borne encephalitis incidence do not correlate with Lyme borreliosis, Austria, 2005 to 2018. Euro Surveill 26(35):2002108

108. Drewes S, Sheikh Ali H, Saxenhofer M et al. (2017) Host-associated absence of human Puumala virus infections in Northern and Eastern Germany. Emerg Infect Dis 23(1):83–86

109. Schlegel M, Klempa B, Auste B et al. (2009) Dobrava-Belgrade virus spillover infections, Germany. Emerg Infect Dis 15(12):2017–2020

110. Hofmann J, Meier M, Enders M et al. (2014) Hantavirus disease in Gemany due to infection with Dobrava-Belgrade virus genotype Kurkino. Clin Microbiol Infect 20(19):O648–55

111. Hofmann J, Kramer S, Herrlinger KR et al. (2021) Tula virus as causative agent of hantavirus disease in immunocompetent person, Germany. Emerg Infect Dis 27(4):1234–1237

112. Schmidt S, Reil D, Jeske K et al. (2021) Spatial and temporal dynamics and molecular evolution of Tula orthohantavirus in German vole populations. Viruses 13(6):1132

113. Hofmann J, Heuser E, Weiss S et al. (2020) Autochthonous ratborne Seoul virus infection in woman with acute kidney injury. Emerg Infect Dis 26(12):3096–3099

114. Weiss S, Klempa B, Tenner B et al. (2019) Prediction of the spatial origin of Puumala virus infections using L segment sequences derived from a generic screening PCR. Viruses 11(8):694

115. Hofmann J, Loyen M, Faber M et al. (2022) Hantavirus-Erkrankungen: Ein Update. Dtsch Med Wochenschr 147(6):312–318

116. Faber M, Krüger DH, Auste B et al. (2019) Molecular and epidemiological characteristics of human Puumala and Dobrava-Belgrade hantavirus infections, Germany, 2001 to 2017. Euro Surveill 24(32):1800675

117. Meining S, Puhlmann H, Hartmann P et al. (2020) Waldzustandsbericht 2020. Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg. https://mlr.baden-wuerttemberg.de/fileadmin/redaktion/m-mlr/intern/dateien/publikationen/Wald/Waldzustandsbericht_2020.pdf (As at 16.12.2022)

118. Princk C, Drewes S, Meyer-Schlinkmann KM et al. (2022) Cluster of human Puumala orthohantavirus infections due to indoor exposure? – An interdisciplinary outbreak investigation. Zoonoses Public Health 69(5):579–586

119. Tersago K, Verhagen R, Servais A et al. (2009) Hantavirus disease (Nephropathia epidemica) in Belgium: Effects of tree seed production and climate. Epidemiol Infect 137(2):250–256

120. Reil D, Rosenfeld UM, Imholt C et al. (2016) Puumala hantavirus infections in bank vole populations: Host and virus dynamics in Central Europe. BMC Ecol 17(1):9

121. Reil D, Imholt C, Drewes S et al. (2016) Environmental conditions in favour of a hantavirus outbreak in 2015 in Germany? Zoonoses Public Health 63(2):83–88

122. Övergaard R, Gemmel P, Karlsson M (2007) Effects of weather conditions on mast year frequency in beech (*Fagus sylvatica* L.) in Sweden. Forestry 80(5):555–565

123. Paar U, Guckland A, Dammann I et al. (2011) Häufigkeit und Intensität der Fruktifikation der Buche. AFZ-DerWald 6/2011:26–29

124. La Bastide JGA, van Vredenburch CLH (1970) Factoren die de zaadproduktie van bomen beinvloeden: Analyse, prognose en consequenties voor de praktijk. Bericht Stichting Bosbouw proefstation, Wageningen. https://edepot.wur.nl/269079 (As at 20.12.2022)

125. Bogdziewicz M (2022) How will global change affect plant reproduction? A framework for mast seeding trends. New Phytol 234(1):14–20

126. Hacket-Pain A, Bogdziewicz M (2021) Climate change and plant reproduction: Trends and drivers of mast seeding change. Philos Trans R Soc Lond B Biol Sci 376(1839):20200379

127. Binder F, Drewes S, Imholt C et al. (2020) Heterogeneous Puumala orthohantavirus situation in endemic regions in Germany in summer 2019. Transbound Emerg Dis 67(2):502–509

128. Sipari S, Khalil H, Magnusson M et al. (2022) Climate change accelerates winter transmission of a zoonotic pathogen. Ambio 51(3):508–517

129. Bolte A, Höhl M, Hennig P et al. (2021) Zukunftsaufgabe Waldanpassung. AFZ-DerWald 4/2021:12–16

130. Nussbaumer A, Meusburger K, Schmitt M et al. (2020) Extreme summer heat and drought lead to early fruit abortion in European beech. Sci Rep 10(1):5334

131. Nationale Expertenkommission "Stechmücken als Überträger von Krankheitserregern" am Friedrich-Loeffler-Institut (2022) Integriertes Management von vektorkompetenten Stechmücken in Deutschland unter Berücksichtigung der Anwendung von Adultiziden. https://www.openagrar.de/servlets/MCRFileNodeServlet/openagrar_derivate_00049699/Handlungsempfehlung_Management_inkl_Anwendung_Adultizide_08-11-2022_bf.pdf (As at 16.12.2022)

132. Robert Koch-Institut (2019) Information zur Vermeidung von Hantavirus-Infektionen. Robert Koch-Institut. https://www.rki.de/DE/Content/InfAZ/H/Hantavirus/Merkblatt_PDF.pdf?__blob=publicationFile (As at 08.12.2022)

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Impact of climate change on waterborne infections and intoxications

Abstract

Progressive climate change holds the potential for increasing human health risks from waterborne infections and intoxications, e.g. through an increase in pathogen concentrations in water bodies, through the establishment of new pathogens or through possible changes in pathogen properties. This paper presents some examples of potential impacts of climate change in Germany. Non-cholera *Vibrio* occur naturally in seawater, but can proliferate significantly in shallow water at elevated temperatures. In the case of *Legionella*, climate change could lead to temporary or longer-term increased incidences of legionellosis due to the combination of warm and wet weather. Higher temperatures in piped cold water or lower temperatures in piped hot water may also create conditions conducive to higher *Legionella* concentrations. In nutrient-rich water bodies, increased concentrations of toxigenic cyanobacteria may occur as temperatures rise. Heavy rainfall following storms or prolonged periods of heat and drought can lead to increased levels of human pathogenic viruses being washed into water bodies. Rising temperatures also pose a potential threat to human health through pathogens causing mycoses and facultatively pathogenic micro-organisms: increased infection rates with non-tuberculous mycobacteria or fungi have been documented after extreme weather events.

This is part of a series of articles that constitute the German Status Report on Climate Change and Health 2023.

NON-CHOLERA VIBRIO · LEGIONELLOSIS · CYANOBACTERIA · ENVIRONMENTAL MICROBES · VIRAL INFECTIONS

1. Introduction

Numerous human pathogens can be transmitted through contact with water. Oral ingestion, inhalation or skin contact with pathogens such as *Legionella*, *Vibrio*, cyanobacteria or non-tuberculous mycobacteria lead to diseases, which can be severe and run fulminant courses. Pathogens causing mycoses and other facultatively pathogenic micro-organisms also present a health hazard.

The consequences of global warming and resulting climate change are expected to have effects on waterborne infections in the future. Longer seasonal warm periods due to hot summers or prolonged warm autumns can lead to an increase in water temperatures in northern latitudes. These increased temperatures can favour the multiplication of pathogens. Such a climatic effect could be shown, for example, for the Baltic Sea by means of satellite data since 1990. An analysis showed that the annual mean temperature of the surface of the entire Baltic Sea has warmed by around 0.8°C over the last 16 years [1]. Storm surges and floods can also spread waterborne germs, especially waterborne viruses and facultatively pathogenic environmental microbes. It can be assumed that these weather phenomena will occur more frequently as climate change progresses.

Many waterborne infections can be acquired during leisure activities. This has far-reaching consequences for human health, as the leisure behaviour of the population may become more oriented towards water-associated activities in the context of rising outdoor temperatures. In this article, the risk of waterborne infections and intoxications in Germany will be discussed using the example of various micro-organisms whose occurrence is influenced by climate change.

The contents to be presented in this article were jointly determined by the authors according to their expert opinions. Appropriate references to current literature have been added, but there is no claim to completeness.

2. Non-cholera *Vibrio*

Vibrio are gram-negative, rod-shaped bacteria that are moderately to markedly halophilic (salt-loving). *Vibrio (V.) cholerae* O1/O139, which can produce the cholera toxin, are probably the best-known representatives of *Vibrio*. They cause epidemic cholera. Cholera is occasionally diagnosed in Germany as a travel-associated infection, but is not endemic in Europe.

However, so-called non-cholera *Vibrio* (NCV) such as *V. parahaemolyticus*, *V. vulnificus*, *V. cholerae* non-O1/non-O139, *V. fluvialis*, *V. furnissii*, *V. alginolyticus*, *V. mimicus* and *V. metschnikovii,* which are also pathogenic to humans, occur as components of the normal bacterial flora in the North Sea and Baltic Sea, and occasionally in somewhat salinic inland waters. The North and Baltic Seas contain slightly different compositions of NCV, presumably due to differences in salinity. In a study investigating water and sediment, it was shown that in the highly saline North Sea, *V. parahaemolyticus* is found more frequently, whereas in the Baltic Sea mainly *V. vulnificus* is detected besides other NCV. *V. cholerae* non-O1/non-O139 is also frequently detectable here [2]. Shallow waters poorly mixed by wind, tides or other currents are particularly affected, as they can heat up strongly when exposed to sunlight. At water temperatures above 20°C, NCV can proliferate in these waters. On the North Sea coast, estuary beaches are particularly susceptible to the occurrence of higher NCV concentrations due to the reduced salinity. On the Baltic Sea coast, 'bodden' waters (briny coastal lagoons in the shelter of islands) in summer and early autumn fulfil many conditions for NCV growth. Predictions of NCV proliferation can be seen in the 'Vibrio map viewer', a tool of the European Centre for Disease Control (ECDC) that uses realtime data on water temperature and sea surface salinity to predict the occurrence of environmental conditions that favour the proliferation of *Vibrio*. [3].

People can become infected with NCV in various ways: they may ingest the pathogens in raw or inadequately heated food of marine origin, such as oysters or other seafood [4]. Another article in this status report discusses climate change impacts on foodborne infections and intoxications in more detail (Dietrich et al. [5]). Pathogens can enter the body when larger wounds, or even very small skin lesions, People with pre-existing conditions are at increased risk of waterborne infections, including older persons and the immunocompromised.

come into contact with water. In this context, infections with *V. vulnificus* are frequently described. Infections through skin injuries occurring directly in the water are rare, yet possible [6, 7] and so are wounds incurred when handling animals, shells and stones to which seawater adheres, for example when processing fish. Especially in children, ear infections with NCV, mainly with *V. cholerae* non-O1/non-O139, occur frequently, e. g. through swimming or bathing in shallow waters.

Depending on the various routes of infection and pathogen species, different clinical pictures manifest in the form of gastroenteritis, wound infections or ear infections; in the case of aspiration of seawater, even pneumonia, caused by *V. vulnificus*, has been described [8, 9]. Gastroenteritis usually does not correspond to extremely severe, rice water-like diarrhoea with a great risk of dehydration typical for the clinical picture of cholera, since NCV lack the cholera toxin. Starting from wounds, or injuries to the skin barrier, the bacterial toxins can cause invasive, cross-tissue, usually purulent infections, requiring urgent surgical treatment [10]. Both wound infections and gastroenteritis can lead to sepsis, which is associated with significant lethality. Rapid medical treatment is necessary. While infections with NCV can affect all age groups, clear risk groups can be identified, particularly in the case of severe wound and soft tissue infections and sepsis: these include older and immunocompromised persons. People with pre-existing conditions such as diabetes mellitus, liver disease (e. g. liver cirrhosis, chronic hepatitis), cancer (e. g. after chemotherapy) and severe heart disease also have an increased risk of symptomatic infection and of a severe course of disease [11]. In contrast, young healthy adults are rarely among the cases recognised in Europe, and they usually do not become severely ill. With rapid, appropriate and adequately dosed antimicrobial therapy, infections can be controlled even in high-risk patients. If left untreated or treated too late, surgical intervention (up to and including amputation of affected limbs) may also be necessary due to the rapid progression of the infection. In case of injuries or visible infections of skin and soft tissues post salt water exposure, a current guideline on skin and soft tissue infections therefore recommends the immediate application of antibiotic combination therapy [12]. Therapy should be started in patients at risk even while the microbiological confirmation of NCV is pending [9]. Patients with gastroenteritis caused by NCV who are at increased risk of sepsis due to pre-existing conditions such as diabetes or liver damage should also receive antibiotic therapy at an early stage.

In the years prior to the introduction of an explicit mandatory notification requirement, up to 20 cases of NCV infections with exposure sites in Germany were reported to the Robert Koch Institute (RKI, Germany's national public health institute) each year. These cases were diagnosed more frequently in the warmer summers of the years 2003, 2006, 2010, 2018 and 2019.

A large study of 63 German cases in the years 2018 and 2019, which had very hot summers, described patients with a clear age and gender distribution (the majority was over 60 years old and predominantly male) as well as seasonality of the infections. Patients had become infected with NCV significantly more often at or in the Baltic Sea than at or in the North Sea. Wound infections were the most frequent form of disease, with the majority (84%) being pre-existing wounds inflamed by seawater contact. Common pre-existing conditions of the mostly older persons were cardiovascular disease, diabetes mellitus or immunodeficiency; 51% of the patients had to be treated in an intensive care unit, and a total of eight patients died in connection with the infection [9].

On 01.03.2020, in addition to a mandatory notification requirement for cholera in Germany, a mandatory notification requirement for infections with other human pathogenic *Vibrio* was included in the German Protection against Infection Act (Infektionsschutzgesetz, IfSG). A subset of the NCV infections reported since 2020 is described in Table 1. A clear seasonality of disease onset in the summer months among the mainly older patients becomes apparent. It is also evident that the majority of infections with NCV are associated with water contact (especially at the Baltic Sea). With advancing climate change an increase in these infections, especially in coastal waters, is to be expected during hot, long summers.

2.1 Influence of climate change on *Vibrio* infections

Climate change affects infections with *Vibrio* in at least two ways:

Since water temperatures above 12°C generally have a favourable effect on the occurrence of *Vibrio*, and NCV can multiply particularly strongly in warm water above 20°C, more frequent longer warm periods contribute to the concentration of pathogens in the water. This concentration can be additionally increased if the water circulation is reduced or even absent due to altered tidal fluctuations, lower frequency of storms or changed influences of other currents. A climate-induced extension of that period of the

Table 1
Excerpt of suspected non-travel-associated NCV infections reported to the Robert Koch Institute since the introduction of a mandatory notification requirement for NCV
Source: SurvNet, database of infectious diseases with mandatory notification requirement in Germany

	2020 (from March)	2021
Cases not explicitly associated with international travel	13 (out of a total of 13 reported NCV infections)	25 (out of a total of 29 reported NCV infections)
Where infection was acquired (where known)	9 x Baltic Sea 1 x North Sea	14 x Baltic Sea 2 x inland waters
Male gender	9 (69%)	16 (64%)
Age range (in years)	22–87, median: 60	8–89, median: 68
Onset of disease July through September	9 (100% of those with onset indicated)	16 (80% of those with onset indicated)
Pathogen	8 x *V. vulnificus* 4 x *V. cholerae* non-O1/non-O139 1 x *V. parahaemolyticus*	14 x *V. vulnificus* 4 x *V. cholerae* non-O1/non-O139 3 x *V. alginolyticus* 2 x *V. parahaemolyticus* 1 x other species 1 x co-infection with 2 species
Forms of disease (where known)	5 x wound infection/sepsis 2 x ear infection	18 x wound infection/sepsis 3 x gastroenteritis 1 x ear infection

NCV = non-cholera *Vibrio*, V. = *Vibrio*

An increase in infections by non-cholera *Vibrio*, especially in the coastal waters of the Baltic Sea, is to be expected as climate change progresses.

year in which high NCV concentrations are to be expected also extends the phase in which vulnerable people in particular can come into contact with the pathogens, e. g. by extending the bathing season. In addition, it should be noted that demographic change is generally increasing the proportion of vulnerable groups in the German population, and presumably also among holidaymakers on German coasts. As a consequence of global warming, it is expected that the surface temperature in the Baltic Sea will increase by about 3°C to 4°C in the next decades [13], which will lead to a general increase of NCV pathogenic to humans in coastal waters.

2.2 Recommendations to limit exposure to NCV

Due to the breadth of this topic, the recommendations presented here focus on wound infections and sepsis, primarily caused by *V. vulnificus,* as these are the most serious NCV infections in Germany. Studies concerning *V. vulnificus* as a human pathogen have already been described in detail, and show a significantly increased risk of certain groups of people becoming infected with this pathogen and becoming seriously ill [14].

(1) Infections with NCV can be reduced if potentially infectious water contact is avoided, in particular, wounds should not be exposed to seawater. Theoretically, it is helpful to opt for water contact with lower infection probabilities, such as wading or swimming at beach sections open to the sea and influenced by tides, instead of particularly poorly mixed and brackish coastal sections such as 'bodden' waters. People who bear the highest risk of a severe course of the disease in the event of infection with NCV would benefit most from these measures, above all senior citizens, especially those with the described pre-existing conditions, e. g. poorly healing wounds on the legs. Severe courses of the disease can be prevented or mitigated by rapid and appropriate treatment.

(2) It is a widespread piece of misinformation that seawater disinfects wounds. Patients with risk factors for severe disease progression should be informed, e. g. by their general practitioners, about the general risks of infection when wounds come into contact with natural waters. Coastal rehabilitation clinics and similar facilities should seasonally actively inform residents about the risks of infection with NCV and provide advice on how to avoid infection. Tourist facilities should also address the relevant risks in a manner appropriate to the target group. Physicians, especially in coastal areas, should consider NCV infections as a differential diagnosis, particularly in the case of wound infections and sepsis requiring immediate treatment after coastal exposures, and initiate treatment with suitable antibiotics as quickly as possible.

3. *Legionella*

Legionnaires' disease (LD) is a form of pneumonia caused by *Legionella*, largely the species *Legionella pneumophila*. Typically, this bacterium is found in water systems or biofilms, but it must be nebulised and then inhaled to cause illness [15]. Epidemiologically, three categories of LD are distinguished: travel-associated, hospital-associated, and community-acquired, i. e. acquired in a personal or work environment. In principle, transmission of *Legionella* is possible through a variety of sources, e. g. aerosols from

Climate change could lead to increases in the incidence of legionellosis.

evaporative cooling systems [16,17] or hot tubs [18], but according to current knowledge, the epidemiologically most important source of infection is domestic drinking water [19]. However, in studies searching for sources of infection with LD, at least half of the sporadic illnesses (i.e. not occurring in the context of an outbreak) remain without a confirmed source of infection [19,20]. A proportion of these could occur – including via alternative routes of transmission – in the context of certain weather conditions (e.g. increased rainfall) [21]. Major outbreaks of LD are relatively rare in Germany and have often been caused by evaporative cooling systems in the past, e.g. 2009/2010 in Ulm [22] or 2013 in Warstein [23]. LD is a seasonal disease, with most cases occurring in the summer and autumn months. Of the three epidemiological groups, seasonality is most pronounced in travel-associated cases, followed by community-acquired cases. Hospital-associated cases, on the other hand, show little seasonality.

In Germany, LD is notifiable according to IfSG. The annual incidence is about 1.9:100,000 inhabitants, corresponding to about 1,500 reported cases per year. However, an unreported number of 15,000 to 30,000 cases is assumed [24]. Community-acquired cases of LD are the most common, accounting for about 70%, followed by travel-associated cases (about 20%) and cases associated with a stay in a hospital or nursing home (about 10%). Older persons, especially males, and people with pre-existing heart, lung or other organ disease are considered to be at risk. Smoking is a strong risk factor [25].

3.1 Influence of climate change on legionellosis

Climate change could affect the frequency of LD occurrence in two ways:

(1) Through environmental factors, which can sometimes mimic outbreaks: increased incidence of LD was associated with various weather conditions in some studies. These included increased humidity [26–29], increased precipitation [26–31], increased air temperature [26,29,31], low air pressure [30], or combinations of these factors. In the Netherlands, outbreak-like increases in incidence have been associated with warm, humid weather conditions [26]. In Germany, there were unexpected increases in case numbers in the summer of 2018 in Bavaria and Baden-Württemberg, which were probably associated with a similar effect. The mechanism of the environmental factor-associated incidence increase is unknown. Some authors have hypothesised that driving cars on wet roads may lead to aerosolisation of puddle water contaminated with *Legionella* [28,32]. This could explain the fact that in a Japanese study, *Legionella* DNA was identified in air samples near busy roads, sometimes even *L. pneumophila* [28]. The amount of *Legionella* DNA correlated with the monthly amount of precipitation. In places where climate change leads to a more frequent coincidence of warm and humid weather, it cannot be ruled out that the incidence of LD may increase and that occasional outbreak-like clusters of cases may occur.

(2) In the long term, through household drinking water: given the rising average air and ground temperatures, it is possible that the base temperature of cold water will increase. Such an effect could lead to increased *Legionella* growth in cold water, which in turn could lead to increased

Legionella concentrations in both cold and hot water. Another factor that could lead to increased *Legionella* growth is the increasing desire of many households to save energy by lowering hot water temperatures, both to protect the climate and to save money as energy prices rise. This could push the incoming hot water temperature into a range, say below 50°C, where *Legionella* growth is not only not suppressed but may even be encouraged. It is reasonable to assume an increased risk in the context of climate change if one accepts the premise that a higher concentration of *Legionella* in drinking water is associated with an increased risk of LD. However, the notion of infective dose paradox has existed for a long time [33], i.e. it has been observed that a higher *Legionella* concentration is not necessarily associated with an increased risk of LD. In a case-control study conducted in Berlin (the LeTriWa study), the strongest risk factor identified at the microbiological level was not *Legionella* concentration, but the presence of virulence-associated (MAb 3/1-positive) *Legionella* in domestic drinking water [19].

3.2 Recommendations to limit the health impact of *Legionella*

There are a number of options for the prevention of LD. In the context of current climate warming, it is important to develop research approaches to further investigate the possible mechanisms, mentioned above, by which climate change influences the incidence of LD.

(1) On the technical side, there is still a considerable need for research. For example, it has been shown that even in the 2011 version of the German Ordinance on the Quality of Water Intended for Human Consumption (Trinkwasserverordnung, TrinkwV), drinking water installations that are not subject to mandatory testing (especially apartments with decentralised drinking water heating, e.g. instantaneous water heaters) may well contain high concentrations of *Legionella* [34]. Furthermore, the LeTriWa study found that virulence-associated *Legionella* were identified not only in drinking water installations subject to mandatory testing, but also in drinking water installations not subject to mandatory testing, and could be associated with the occurrence of LD [19, 34–36]. The influence of water temperature in drinking water installations, *Legionella* concentration and strain type on the risk of LD needs to be investigated. New or modified prevention options could result from the findings, and their effectiveness should be tested.

(2) It is also important to determine which preventive factors or behaviours that can be influenced by individuals help to prevent the transmission of LD. In the LeTriWa study, it was found that personal knowledge of *Legionella* and its characteristics as well as individual, preventive behaviours can reduce the risk (Buchholz et al.; data not published). One behaviour identified as significant was letting water run before use.

(3) Since the negative and very strong effect of smoking as a risk factor for the occurrence of LD is well established, campaigns to reduce smoking against this background may be effective. Further research should investigate how the co-benefits of reduced tobacco consumption can be better communicated.

4. Cyanobacteria

Cyanobacteria are gram-negative bacteria, but differ from other bacteria in their ability to perform oxigenic photosynthesis. Because of their ecology, which is similar to that of algae, and the possession of accessory pigments such as the blue phycocyanin, cyanobacteria are sometimes called 'blue-green algae'. They colonise various habitats worldwide and are a natural part of the biotic community in water bodies. However, in waters with high nutrient concentrations (phosphorus, nitrogen), cyanobacteria can proliferate massively, with negative effects on the ecosystem and on the use of these waters as a drinking water resource or bathing water, especially because of the ability of some cyanobacteria to produce potent toxins [37].

Especially those cyanobacteria commonly found in freshwater such as *Microcystis*, *Planktothrix, Aphanizomenon*, and *Dolichospermum* are potentially toxic and form large populations, so-called algal blooms, under favourable conditions. Not all genotypes of cyanobacteria can produce toxins, and populations usually consist of a mixture of non-toxic and toxic genotypes, the latter with sometimes marked differences in toxin content. Toxin concentration in a water body depends largely on the biomass of cyanobacteria, but also on the genotype composition. Environmental factors influence both the occurrence and extent of cyanobacterial populations as well as genotype composition, which can thus change over the course of the season.

Cyanobacteria can be harmful due to their ability to produce toxins, but do not multiply in the human body. The most important cyanobacterial toxin groups include hepatotoxins (microcystins, nodularins, cylindrospermopsins) and neurotoxins (anatoxins, saxitoxins) [37]. The systemic effect of the toxins occurs exclusively by oral uptake; uptake via the skin is not likely. For hepatotoxins, chronic toxicity is of primary importance, whereas the health risk for neurotoxins is primarily due to their acute oral toxicity, which may be pronounced.

Allergic effects of cyanotoxins have not been demonstrated so far, but irritating and sensitising properties have been observed in skin contact with unnaturally high concentrations of cylindrospermopsin. The symptoms often reported in connection with cyanobacterial contact, such as mucosal irritation, nausea, and respiratory illness, are most likely not caused by cyanotoxins, but are due to other cell components, bacteria accompanying cyanobacteria, or other pathogenic organisms in the water [37]. A clear causality in the case of rather unspecific symptoms is usually not demonstrable due to the large number of possible causes.

Humans may be exposed to cyanobacteria and their cyanotoxins during recreational activities in waters with algal blooms, but also through drinking water if drinking water treatment does not effectively remove cyanotoxins from infested waters. Furthermore, they may be present in food (e.g. fish, food supplements made from cyanobacteria). Clearly documented serious illnesses or even deaths in humans due to cyanotoxin ingestion are only known in isolated cases internationally, and not at all in Germany.

4.1 Influence of climate change on cyanobacteria

The primary cause of mass occurrence of cyanobacteria is increased nutrient concentrations (phosphorus, nitrogen) in the water body. The effects of climate change can in-

Climate change will lead to an increase in (potentially toxic) cyanobacteria in some water bodies.

crease or decrease the occurrence of cyanobacteria. In nutrient-rich waters, for example, stable stratification caused by high temperatures has a favourable effect on growth. In contrast, in water bodies with lower nutrient levels, falling water levels due to low precipitation on the one hand and nutrient run-off from agricultural land during heavy rainfall events on the other hand can lead to an increase in nutrients and thus to more cyanobacteria [38, 39]. However, pronounced stratification of a water body with incomplete mixing can lead to a decrease in nutrients, which in turn can negatively impact cyanobacteria. Heavy rainfall and wind can also have a detrimental effect on their proliferation [40]. Since the data on the influence of environmental factors on the toxin content of a population are not unambiguous, it is not yet possible to assess the overall influence of climate change.

In summary, it is very likely that climate change will lead to significant changes in ecological processes in water bodies. It is currently difficult to estimate how these changes will affect individual water bodies: in some waters this will lead to more frequent and more pronounced cyanobacterial blooms, but in others it will not. As this depends on the trophic state and morphometry of a water body as well as regional weather phenomena, no general influence of climate change on cyanobacterial blooms can be derived for all water bodies [39].

4.2 Recommendations to limit the health impact of cyanobacteria

For the most important toxins, the World Health Organization (WHO) has set guideline values for both drinking water and bathing water [37]. The EU Drinking Water Directive, revised in 2021, adopts the WHO guideline value of 1 µg/l for microcystin-LR; this is to be transposed into national law by 2023. For bathing waters, article 8, 'Cyanobacterial risks', of the EU Bathing Water Directive regulates the risk assessment and communication concerning toxic cyanobacteria.

For drinking water, no risk from cyanotoxins is to be expected due to the low proportion of treated surface water in Germany and effective drinking water treatment processes in accordance with legal requirements. On the other hand, bathing in waters heavily infested with cyanobacteria may pose a health risk, as most cyanobacterial blooms in Germany contain cyanotoxins. Especially the ingestion of larger quantities of contaminated water must be avoided, which is why children playing in the surf (due to their frequent hand-mouth contact), children learning to swim, or people engaging in water sports exposed to aerosols (e.g. when water skiing) belong to the risk group. However, the largest amounts of water are probably ingested in bathing accidents (near-drowning).

In order to protect bathers, bathing waters reported to the EU are examined for the presence of cyanobacteria and, depending on the extent of contamination, warnings or even a bathing ban are issued [41]. In addition, education is necessary for responsible action by individuals, since water bodies cannot always be examined promptly and dense algal blooms close to the shore can occur sporadically.

Finally, the most sustainable protection against cyanobacteria is to prevent their (mass) proliferation in the water body. This can only be achieved by ensuring sufficiently low concentrations of nutrients and is also imperative in order to control the effects of climate change [42].

Extreme weather events can lead to increased exposure to aquatic and terrestrial pathogens.

5. Waterborne viral infections

In contrast to the clearly traceable effect of climate change on the proliferation of vector-borne viruses (see the article in this status report on the effects of climate change on vector-borne infectious diseases, Beermann et al. [43]), the effects of climate change on human pathogenic enteric viruses are not immediately apparent. Gastrointestinal infections caused by human pathogenic enteric viruses, such as noroviruses, rotaviruses, enteroviruses, and hepatitis A and hepatitis E viruses, which can cause waterborne infections through contamination of water bodies, have declined in Europe in recent decades due to hygienic measures. Due to the COVID-19 pandemic and the resulting hygiene measures (reduced contacts, lockdowns and the wearing of face masks), which led to a general reduction in the circulation of human pathogenic viruses, little attention has been paid to changes in the seasonal occurrence and biodiversity of enteric viruses in water bodies, which can be significant.

5.1 Influence of climate change on waterborne viral infections

Waterborne infections by enteric viruses are strongly affected by the secondary effects of climate change [44]. Human pathogenic viruses that enter the aquatic environment can often maintain their infectivity for long periods of time, depending on the stability of their viral capsid. However, the viruses can no longer replicate in water. Therefore, an increase in water temperature usually does not play a central role for enteric viruses. However, increased concentrations of the pathogens in water are caused mainly by climate change-induced storms, prolonged periods of heat with drought, and heavy rainfall. Such extreme weather events often lead to increased run-off of pathogenic viruses into water bodies and thus to the deterioration of their hygienic quality [45]. The risk of infection may also be increased during dry periods due to reduced water volume and flow rates in rivers. These temporarily increased viral loads lead to increased risks of transmission of waterborne infections and gastrointestinal diseases. Extreme weather events with heavy rainfall and flooding are also becoming more frequent in Germany, as demonstrated by the floods in Rhineland-Palatinate and North Rhine-Westphalia in July 2021, which led to an increased risk of infections with gastrointestinal pathogens due to mixing of wastewater and floodwater. The influence on health of extreme weather events caused by climate change is considered in more detail in another article in this status report (Butsch et al. [46]).

5.2 Recommendations to limit the health impact of waterborne viral infections

(1) The majority of newly discovered or recurrent pathogens are viruses [47]. Due to changes in climatic conditions, the emergence of new zoonotic pathogens and an increase in new waterborne viral infections can also be expected in water. Efficient methods for the detection of pathogens and their elimination must therefore be developed.

(2) Furthermore, the influence of climate change on observed changes in the seasonal occurrence of potentially pathogenic viruses in water bodies needs to be investigated in more detail. Water-based epidemiology, as

well as the One Health and Planetary Health concepts, which include a consideration of environmental conditions on infection events, offer good frameworks for this. Especially after extreme weather conditions, increased monitoring programmes on the occurrence of pathogenic viruses in water bodies may detect climate-related increases in waterborne virus infections at an early stage and reduce or prevent them by uncovering possible chains of infection.

6. Facultatively pathogenic environmental microbes

Numerous facultatively pathogenic micro-organisms (e.g. fungi, amoebae, bacteria, mycobacteria) are part of polymicrobial communities in various environmental habitats (e.g. in soil and water). Compared to non-pathogenic microbes, they are characterised by thermotolerance, i.e. the ability to grow at human body temperature. In contrast to infections caused by classical bacterial pathogens, the diagnosis, treatment and control of infections caused by such environmental microbes present particular difficulties. Microbiological diagnosis is limited due to often slow growth and ubiquitous occurrence. Many of these pathogens are difficult to treat due to antimicrobial resistance. Longer incubation periods may lead to outbreaks being detected late or not at all without molecular typing.

6.1 Influence of climate change on facultatively pathogenic environmental microbes

It has been hypothesised that the increase in environmental temperatures provides a selection advantage for certain facultatively pathogenic environmental microbes. In addition, an adaptation of previously non-pathogenic fungi to higher temperatures has been reported, and as a result, these fungi can be considered infectious agents [48]. The establishment of micro-organisms from warm tropical regions in the temperate climate zones of the North American west coast, observed in an outbreak of the tropical fungal pathogen *Cryptococcus gattii*, demonstrates the dynamics of habitat change [49].

Especially after extreme weather events, humans may be increasingly exposed to these micro-organisms due to such changes in pathogen characteristics and distribution. After floods, for example, events like higher rates of infection with non-tuberculous mycobacteria or fungi are increasingly being documented, supporting this hypothesis (e.g. [49–51]).

6.2 Recommendations to limit the health impact of facultatively pathogenic environmental microbes

(1) Comprehensive monitoring of the microbial population is necessary in order to document changes in microbial components of environmental habitats and assess risk, e.g. by metagenomic surveillance of micro-organisms in environmental samples using methods that are also suitable for these pathogen groups [52].

(2) Improving diagnostic methods (e.g. polymerase chain reaction (PCR), sequencing) for these pathogens and polymicrobial infections are crucial for successful therapeutic strategies.

(3) The development of molecular typing schemes is necessary for the detection and containment of outbreaks.

7. Conclusion and outlook

Global warming and progressive climate change have far-reaching impacts on human health. Waterborne infections and intoxications pose an increased risk in this context. Pathogens that can cause human infections and intoxications through contact with water may become more prevalent as water temperatures rise. Extreme weather events can also lead to increased exposure to aquatic and terrestrial pathogens. Due to changes in climatic conditions, the emergence of new zoonotic pathogens in water and an increase in new waterborne viral infections can also be expected. Climatic changes may also create selection advantages for thermotolerant facultatively pathogenic microbes, and temperature adaptation of previously non-pathogenic micro-organisms may occur.

In this article, we give recommendations to better protect human health from waterborne infections and intoxications in three broad categories: measures to reduce the risk of exposure, education, and research.

Reducing the risk of exposure is the first priority, especially for infections with NCV, but also for cyanobacteria and cyanotoxins. The most sustainable protection against cyanobacteria is to prevent their (mass) proliferation in water. This can only be achieved by ensuring sufficiently low concentrations of nutrients to protect bathers. To prevent infections with NCV and minimise the risk of severe disease, it is important for persons belonging to risk groups to avoid potentially infectious water contact and to seek prompt treatment with antibiotics if infection is suspected.

Since people with pre-existing conditions, immunocompromised and older persons have an increased risk for waterborne infections, improved education about the risks is of great importance. Medical and tourist facilities at the North Sea and Baltic Sea also need to be informed about the increasing risks, especially regarding NCV infections.

Research efforts on risk factors and their control should be increased, for example regarding tobacco consumption as a risk factor for LD. Efficient methods for the detection of different and novel pathogens and their elimination should be developed. Particularly after extreme weather conditions, wide-ranging studies on the occurrence of pathogenic viruses and other microbes in bodies of water may be able to document potential hazards that can arise and thus enable climate-related increases in waterborne infections to be detected at an early stage.

Joint efforts by many actors are therefore required to reduce the increasing risk to human health from waterborne infections and intoxications that can be expected in the context of climate change.

Changes in climatic factors can lead to a selection advantage for thermotolerant facultatively pathogenic microbes as well as to a temperature adaptation of previously non-pathogenic micro-organisms.

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References

1. Leibniz Institute for Baltic Sea Research Warnemünde (2022) Fact sheet on climate change and its impacts in the Baltic Sea region. https://www.io-warnemuende.de/focus-details/items/fact-sheet-on-climate-change-and-its-impacts-in-the-baltic-sea-region.html (As at 06.01.2023)
2. Fleischmann S, Herrig I, Wesp J et al. (2022) Prevalence and distribution of potentially human pathogenic *Vibrio* spp. on German North and Baltic Sea Coasts. Front Cell Infect Microbiol 12:846819
3. ECDC (2022) ECDC Geoportal – Vibrio Map Viewer. https://geoportal.ecdc.europa.eu/vibriomapviewer/ (As at 06.01.2023)
4. Vu TTT, Alter T, Huehn S (2018) Prevalence of *Vibrio* spp. in retail seafood in Berlin, Germany. J Food Prot 81(4):593–597
5. Dietrich J, Hammerl JA, Johne A et al. (2023) Impact of climate change on foodborne infections and intoxications. J Health Monit 8(S3):78–92. www.rki.de/jhealthmonit-en (As at 01.06.2023)
6. Brehm TT, Berneking L, Rohde H et al. (2020) Wound infection with *Vibrio harveyi* following a traumatic leg amputation after a motorboat propeller injury in Mallorca, Spain: A case report and review of literature. BMC Infect Dis 20(1):104
7. Hecht J, Borowiak M, Fortmeier B et al. (2022) Case Report: *Vibrio fluvialis* isolated from a wound infection after a piercing trauma in the Baltic Sea. Access Microbiol 4(1):000312
8. Brehm TT, Berneking L, Sena Martins M et al. (2021) Heat-wave-associated *Vibrio* infections in Germany, 2018 and 2019. Euro Surveill 26(41):2002041.
9. Brehm TT, Dupke S, Hauk G et al. (2021) Non-cholera Vibrio species – Currently still rare but growing danger of infection in the North Sea and the Baltic Sea. Internist (Berl) 62(8):876–886
10. Meyer HL, Polan C, Burggraf M et al. (2022) "The Baltic Sea Germ": A case report of necrotizing fasciitis following *Vibrio vulnificus* infection. Case Rep Orthop 2022:5908666
11. Metelmann C, Metelmann B, Grundling M et al. (2020) *Vibrio vulnificus*, an increasing threat of sepsis in Germany? Anaesthesist 69(9):672–678

12. Sunderkötter C, Becker K, Eckmann C et al. (2019) Haut- und Weichgewebeinfektionen. In: Paul-Ehrlich-Gesellschaft für Chemotherapie e. V. (eds) S2k Leitlinie: Kalkulierte parenterale Initialtherapie bakterieller Erkrankungen bei Erwachsenen – Update 2018, P. 173–227. https://register.awmf.org/de/leitlinien/detail/082–006 (As at 06.01.2023)
13. Meier HEM, Dieterich C, Gröger M (2021) Natural variability is a large source of uncertainty in future projections of hypoxia in the Baltic Sea. Commun Earth Environ 2(50):1–13
14. Baker-Austin C, Oliver JD (2018) *Vibrio vulnificus*: New insights into a deadly opportunistic pathogen. Environ Microbiol 20(2):423–430
15. Prussin AJ 2nd, Schwake DO, Marr LC (2017) Ten questions concerning the aerosolization and transmission of *Legionella* in the built environment. Build Environ 123:684–695
16. Walser SM, Gerstner DG, Brenner B et al. (2014) Assessing the environmental health relevance of cooling towers – A systematic review of legionellosis outbreaks. Int J Hyg Environ Health 217(2–3):145–154
17. Ricketts KD, Joseph CA, Lee JV et al. (2012) Wet cooling systems as a source of sporadic Legionnaires' disease: A geographical analysis of data for England and Wales, 1996–2006. J Epidemiol Community Health 66(7):618–623.
18. Jernigan DB, Hofmann J, Cetron MS et al (1996) Outbreak of Legionnaires' disease among cruise ship passengers exposed to a contaminated whirlpool spa. Lancet 347(9000):494–499
19. Buchholz U, Jahn HJ, Brodhun B et al. (2020) Source attribution of community-acquired cases of Legionnaires' disease-results from the German LeTriWa study; Berlin, 2016–2019. PLoS One 15(11):e0241724
20. Den Boer JW, Euser SM, Brandsema P et al. (2015) Results from the National Legionella Outbreak Detection Program, the Netherlands, 2002–2012. Emerg Infect Dis 21(7):1167–1173.
21. Sakamoto R (2015) Legionnaire's disease, weather and climate. Bull World Health Organ 93(6):435–436
22. von Baum H, Harter G, Essig A et al. (2010) Preliminary report: Outbreak of Legionnaires disease in the cities of Ulm and Neu-Ulm in Germany, December 2009 – January 2010. Euro Surveill 15(4):19472
23. Maisa A, Brockmann A, Renken F et al. (2015) Epidemiological investigation and case-control study: A Legionnaires' disease outbreak associated with cooling towers in Warstein, Germany, August-September 2013. Euro Surveill 20(46):pii=30046
24. von Baum H, Ewig S, Marre R et al. (2008) Community-acquired *Legionella* pneumonia: New insights from the German competence network for community acquired pneumonia. Clin Infect Dis 46(9):1356–1364
25. Phin N, Parry-Ford F, Harrison T et al. (2014) Epidemiology and clinical management of Legionnaires' disease. Lancet Infect Dis 14(10):1011–1021
26. Brandsema PS, Euser SM, Karagiannis I et al. (2014) Summer increase of Legionnaires' disease 2010 in the Netherlands associated with weather conditions and implications for source finding. Epidemiol Infect 142(11):2360–2371
27. Fisman DN, Lim S, Wellenius GA et al. (2005) It's not the heat, it's the humidity: Wet weather increases legionellosis risk in the greater Philadelphia metropolitan area. J Infect Dis 192(12):2066–2073
28. Kanatani JI, Watahiki M, Kimata K et al. (2021) Detection of *Legionella* species, the influence of precipitation on the amount of *Legionella* DNA, and bacterial microbiome in aerosols from outdoor sites near asphalt roads in Toyama Prefecture, Japan. BMC Microbiol 21(1):215
29. Karagiannis I, Brandsema P, van der Sande M (2009) Warm, wet weather associated with increased Legionnaires' disease incidence in The Netherlands. Epidemiol Infect 137(2):181–187
30. Beaute J, Sandin S, Uldum SA et al. (2016) Short-term effects of atmospheric pressure, temperature, and rainfall on notification rate of community-acquired Legionnaires' disease in four European countries. Epidemiol Infect 144(16):3483–3493
31. Han XY (2021) Effects of climate changes and road exposure on the rapidly rising legionellosis incidence rates in the United States. PLoS One 16(4):e0250364
32. van Heijnsbergen E, de Roda Husman AM, Lodder WJ et al. (2014) Viable *Legionella pneumophila* bacteria in natural soil and rainwater puddles. J Appl Microbiol 117(3):882–890
33. O'Brien SJ, Bhopal RS (1993) Legionnaires' disease: The infective dose paradox. Lancet 342(8862):5–6

34. Buchholz U, Lehfeld AS, Brodhun B et al. (2022) Einfluss der häuslichen Trinkwasser-Installation auf das Risiko, an Legionärskrankheit zu erkranken. Epid Bull (35):3–17

35. Lehfeld AS, Jahn HJ, Brodhun B et al. (2022) Infektionsquellensuche bei ambulant erworbenen Fällen von Legionärskrankheit – Ergebnisse der LeTriWa-Studie; Berlin, 2016–2020 – Teil 2 (Ergebnisse und Diskussion). Epid Bull (28):3–16

36. Buchholz U, Lehfeld AS, Jahn HJ et al. (2022) Infektionsquellensuche bei ambulant erworbenen Fällen von Legionärskrankheit – Ergebnisse der LeTriWa-Studie; Berlin, 2016–2020 – Teil 1 (Studienmethodik). Epid Bull (27):13–22

37. Chorus I, Welker M (eds) (2021) Toxic cyanobacteria in water: A guide to their public health consequences, monitoring and management. CRC Press, on behalf of the World Health Organization, Geneva, Boca Raton (FL).

38. Rigosi A, Carey CC, Ibelings BW et al. (2014) The interaction between climate warming and eutrophication to promote cyanobacteria is dependent on trophic state and varies among taxa. Limnol Oceanogr 59:99–114

39. Ibelings BW, Kurmayer R, Azevedo SMFO et al. (2021) Understanding the occurrence of cyanobacteria and cyanotoxins. In: Chorus I, Welker M (eds) Toxic cyanobacteria in water: A guide to their public health consequences, monitoring and management. CRC Press, on behalf of the World Health Organization, Geneva, Boca Raton (FL), pp. 213–294.

40. Salmaso N, Boscaini A, Capelli C et al. (2018) Ongoing ecological shifts in a large lake are driven by climate change and eutrophication: Evidence from a three-decade study in Lake Garda. Hydrobiologia 824:177–195

41. Umweltbundesamt (2015) Empfehlung zum Schutz von Badenden vor Cyanobakterien-Toxinen. Bundesgesundheitsbl 58:908–920

42. Fastner J, Abella S, Litt A et al. (2016) Combating cyanobacterial proliferation by avoiding or treating inflows with high P load – Experiences from eight case studies. Aquat Ecol 50:367–383

43. Beermann S, Dobler G, Faber M et al. (2023) Impact of climate change on vector- and rodent-borne infectious diseases. J Health Monit 8(S3):33–61. www.rki.de/jhealthmonit-en (As at 01.06.2023)

44. Semenza JC, Rocklov J, Ebi KL (2022) Climate change and cascading risks from infectious disease. Infect Dis Ther 11(4):1371–1390

45. Karthe D (2015) Bedeutung hydrometeorologischer Extremereignisse im Kontext des Klimawandels für die Trinkwasserhygiene in Deutschland und Mitteleuropa. Hydrologie und Wasserbewirtschaftung 59(5):264–270

46. Butsch C, Beckers LM, Nilson E et al. (forthcoming) Health impacts of extreme weather events – Cascading risks in a changing climate. J Health Monit www.rki.de/jhealthmonit-en

47. Nichol ST, Arikawa J, Kawaoka Y (2000) Emerging viral diseases. Proc Natl Acad Sci U S A 97(23):12411–12412

48. Garcia-Solache MA, Casadevall A (2010) Global warming will bring new fungal diseases for mammals. mBio 1(1):e00061–10

49. Engelthaler DM, Casadevall A (2019) On the emergence of *Cryptococcus gattii* in the Pacific Northwest: Ballast tanks, tsunamis, and black swans. mBio 10(5):e02193–19

50. Benedict K, Park BJ (2014) Invasive fungal infections after natural disasters. Emerg Infect Dis 20(3):349–355

51. Honda JR, Bernhard JN, Chan ED (2015) Natural disasters and nontuberculous mycobacteria: A recipe for increased disease? Chest 147(2):304–308

52. Ko KKK, Chng KR, Nagarajan N (2022) Metagenomics-enabled microbial surveillance. Nat Microbiol 7(4):486–496

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Impact of climate change on foodborne infections and intoxications

Abstract

Background: Temperature, precipitation, and humidity are important factors that can influence the spread, reproduction, and survival of pathogens. Climate change affects these factors, resulting in higher air and water temperatures, increased precipitation, or water scarcity. Climate change may thus have an increasing impact on many infectious diseases.

Methods: The present review considers those foodborne pathogens and toxins in animal and plant foods that are most relevant in Germany, on the basis of a selective literature review: the bacterial pathogens of the genera *Salmonella*, *Campylobacter* and *Vibrio*, parasites of the genera *Cryptosporidium* and *Giardia*, and marine biotoxins.

Results: As climate change continues to progress, all infections and intoxications discussed here can be expected to increase in Germany.

Conclusions: The expected increase in foodborne infections and intoxications presents a growing public health risk in Germany.

This is part of a series of articles that constitute the German Status Report on Climate Change and Health 2023.

CAMPYLOBACTER · SALMONELLA · VIBRIO · CRYPTOSPORIDIUM · GIARDIA · MARINE BIOTOXINS · ONE HEALTH

1. Introduction

Temperature, precipitation, humidity, and soil properties are important environmental factors that influence the spread and survival of zoonotic pathogens. Changes in these environmental factors as a result of climate change, such as permanently elevated ambient temperatures, increasing precipitation, but also water scarcity, may contribute to the spread and survival of pathogens. Climate change may thus exert an increasing influence on more than half of all infectious diseases [1]. This is not only true for already existing, i. e. endemic, infectious agents; climatic changes also favour the establishment of novel infectious agents (emergence) as well as the return of pathogens suppressed in the past (re-emergence). For example, in the future, agriculture may have to rely more frequently on treated wastewater due to water scarcity, which will be exacerbated by climate change. This poses a number of risks to food safety, including contamination of irrigated produce by various types of pathogens [2].

This review addresses hazards to human health posed by the most important foodborne bacteria, parasites and

The number of infections with germs such as *Salmonella* or *Campylobacter* correlates positively with maximum temperature and precipitation amounts.

marine biotoxins in Germany and presents recommendations for reducing the risks. For example, the risk of all infections discussed here can be reduced by observing good hygiene during food preparation (kitchen hygiene) and adherence to cold chains.

Since viruses play a minor role in the impact of climatic changes on foodborne infections, they are not further discussed in this article. Their importance in the context of climate change is discussed in detail in other parts of this status report, e.g. in connection with vector-borne infectious diseases (Beermann et al. [3]).

2. Bacteria

2.1 Campylobacter

Bacteria of the genus *Campylobacter* (*C.*) cause an intestinal infection typically associated with abdominal pain and watery, occasionally bloody diarrhoea. Rare complications may include joint inflammation and Guillain-Barré syndrome, a nerve disease associated with paralysis. Even a low infectious dose of ≥500 germs can trigger a *Campylobacter* infection. Approximately 50,000 to 70,000 cases are reported to the Robert Koch Institute (RKI, Germany's national public health institute) annually. For years, *Campylobacter* enteritis has been the most common bacterial diarrhoeal disease in Germany that has a mandatory notification requirement as per the German Protection against Infection Act (IfSG). The most important *Campylobacter* species pathogenic to humans are *C. jejuni* and *C. coli*. Transmission to humans occurs primarily via contaminated food of animal origin. In particular, consumption of contaminated chicken meat is a significant risk factor for *Campylobacter* infection [4–6]. Transmission to humans is also possible via other foods like non-pasteurised milk. Unlike *Salmonella*, *Campylobacter* is considered unlikely to multiply in food because of its microbiological characteristics (growth under microaerobic conditions, i.e. reduced oxygen concentration in the atmosphere, and at temperatures of 30°C to 42°C) [7]. *Campylobacter* infections via contaminated drinking water or bathing water contaminated with animal faeces have also been described [8, 9].

Climate influence on *Campylobacter* infections

Campylobacter enteritis infections typically follow a seasonal course, with the highest number of cases occurring in the summer months from July to September, including non-travel-associated infections. With progressive warming as a result of climate change and the associated prolonged warm periods, an increase in *Campylobacter* cases in humans is therefore expected.

It is conceivable that during the summer months, increased temperatures lead to higher *Campylobacter* prevalence in poultry flocks and thus higher exposure of consumers via consumption of poultry meat, although data on this are not consistent [10–14].

Altered consumption and recreational behaviours during the summer months have an important indirect effect on the increase in human infections, if they are associated with increased exposure, thus promoting infections, such as more frequent barbecuing of poultry and other meats, or swimming in surface waters [14, 15].

An association of human *Campylobacter* infections has been linked not only to temperature [16, 17] but also to the amount of precipitation in the days preceding the onset of illness [18, 19]. An increase in *Campylobacter* infections and *Campylobacter* enteritis outbreaks has been observed after heavy rains and flooding, likely due to increased exposure via faecal-contaminated surface water or contaminated drinking water [9, 20]. In contrast, *Campylobacter* cases are expected to decrease after periods of drought [18, 19].

With increasing water scarcity as a result of climate change, it is conceivable that treated wastewater, which may be contaminated with pathogens from animal or human faeces, will be used more frequently for irrigation of plant-based foods [21]. Increasing contamination of plant-based foods with gastrointestinal pathogens, including *Campylobacter*, would be expected via this route, thus compromising food safety [21]. European Union (EU) Regulation 2020/741 is intended to counteract this and regulates minimum standards for the use of treated wastewater in agricultural irrigation (Info box).

In a model calculation, the effect of increasing temperature and precipitation on the number of *Campylobacter* cases in Scandinavia was estimated. A doubling of *Campylobacter* cases by the year 2080 was predicted for Denmark, Finland, Norway, and Sweden [19]. Further scientific studies are needed to better understand the multifactorial, direct and indirect relationships between climatic changes and *Campylobacter* disease cases.

2.2 *Salmonella*

The bacteria of the genus *Salmonella* are zoonotic agents that can be transmitted directly or indirectly between humans and animals. They are widely distributed in nature. The main reservoir for *Salmonella* is warm-blooded animals, including livestock and wildlife. *Salmonella* also occurs in cold-blooded animals, such as reptiles or insects, which can act as vectors and transmit *Salmonella* to warm-blood-

Info box
EU regulation on water reuse

Climatic changes are increasing the pressure on water resources in Germany and Europe. To counter this pressure, Regulation (EU) 2020/741 established minimum requirements for the use of treated wastewater in agricultural irrigation. It came into effect on June 26, 2020, and will apply to all member states of the European Union from June 26, 2023.

The regulation is intended to reduce water scarcity in the European Union as a result of climate change by reusing water for agricultural irrigation and to facilitate implementation by the member states with uniform requirements. The aim is to achieve a high level of protection for the environment and for human and animal health, and to promote the circular economy [22].

The regulation on minimum requirements for water reuse is limited to agricultural irrigation. In addition to uniform minimum requirements for water quality and monitoring, risk management and provisions for data transparency are the main elements of the regulation [22]. In this context, the German Federal Institute for Risk Assessment (BfR) published opinions on possible risks associated with the reuse of treated wastewater for irrigation of edible crops [23–25]. Even wastewater that has already been treated may still contain parasites, bacteria and viruses in pathogenic concentrations. Therefore, particular care should be taken to ensure that plant parts that are usually consumed raw do not come into direct contact with irrigation water or, if this cannot be safely avoided, should continue to be irrigated with potable water. Persons belonging to risk groups are advised against consumption of such raw foods.

ed animals or humans. Although most salmonellae do not usually cause symptoms in animals, they can cause mild to severe health problems in humans. Human salmonellosis is often accompanied by fever, nausea, vomiting, abdominal pain, and headache, but signs of illness may be completely absent.

In Germany, salmonellosis is the second most frequently reported bacterial foodborne infection in humans after campylobacteriosis; *Salmonella (S.) enterica* is an important cause of foodborne outbreaks. Among these, *S.* Enteritidis and *S.* Typhimurium are the most common serovars, together accounting for approximately 75% of all reported salmonellosis cases [26]. Poultry is presumed the most important source of *Salmonella* infections in humans. In particular, eggs and egg products play a predominant role. Pork and pork products represent another important source [27, 28]. Increasingly, *Salmonella* infections are also reported to be associated with the consumption of foods of non-animal origin [27, 29]. Among these, raw leafy vegetables, onion and stem vegetables, tomatoes, and melons were the most commonly affected products. Contamination of these products with *Salmonella* can occur both before harvest (through faecal matter, irrigation water, dust, insects, etc.) and after harvest (through harvesting equipment, transport containers, insects, dust, rinsing water, ice, transport vehicles, processing equipment) [30].

Climate influence on *Salmonella* infections

In Europe, most salmonellosis cases are reported during the summer months [28]. The incidence of *Salmonella* is often lower in northern countries than in countries located in warmer climates.

Ambient temperature can influence the development of *Salmonella* at different stages of the food chain: e.g. bacterial contamination during raw food production, transport, and improper storage [31]. The optimal temperature for *Salmonella* growth is between 35°C and 37°C; below 15°C, growth of *Salmonella* is greatly reduced. Consequently, *Salmonella* multiply faster at higher temperatures. The significant correlation between outdoor temperatures and outbreaks caused by *Salmonella* has been known for some time. Studies have reported the increase of salmonellosis, as well as other bacterial enteric diseases, with increasing temperatures [32]. According to Zhang et al. [31], an increase of 8.8% in the number of weekly cases can be expected for a 1°C increase in the mean weekly maximum temperature. With a 1°C increase in the mean weekly minimum temperature, a 5.8% increase in the weekly number of cases can be expected.

Temperature can affect the transmission of *Salmonella* to humans through several pathways; by directly affecting the multiplication of *Salmonella* and by indirectly affecting eating habits during hot days. The favoured growth of *Salmonella* at higher temperatures leads to higher concentrations of *Salmonella* in contaminated foods during the warmer months. Among other things, this has to do with poor food preparation and refrigeration during barbecues or picnics, which are also more common during these months. Elevated ambient temperatures increase the risk of cold chain disruption, which can have a significant impact on the microbiological status of food.

Zhang et al. [33] found a strong correlation between drinking water quality, precipitation and gastroenteritis, where maximum and minimum temperatures, relative humidity and precipitation correlated positively with the number of salmonellosis cases.

In areas with increased rainfall, water quality could deteriorate. Heavy rains can increase run-off in rivers and lakes, washing sediment, pollutants, refuse, animal waste, and other materials into water supplies. Severe flooding can inundate wastewater treatment plants. This can lead to contamination of human, animal, and farm environments by bacteria in human sewage that are not only infectious, but can also be resistant to antimicrobial agents. Another article in this status report discusses this issue separately in the context of climate change impacts on health due to extreme weather events (Butsch et al. [34]).

2.3 *Vibrio*

Vibrio are environmental bacteria that colonise saline and brackish water bodies as well as wetlands worldwide, but can also occur in the microbial flora of aquatic animals. For humans, water contact and ingestion of *Vibrio (V.)*-containing seafood (fish, marine animals) can be problematic. As bacterial contaminants, *V. cholerae*, *V. vulnificus,* and *V. parahaemolyticus* in particular can cause infections [35, 36]. The significance of each species for humans varies regionally and is linked to area-specific factors, such as the salinity of water bodies, air and water temperatures, and fluctuations to which they are subject [37]. The genus *Vibrio* includes more than 135 species [38], three of which are largely causative of intestinal (e.g. gastroenteritis) or extraintestinal infections (e.g. middle ear infection) [35]. *V. cholerae* serotypes O1/O139, which produce the cholera toxin, are significant worldwide, as they can lead to pandemic cholera outbreaks in tropical and subtropical regions with poor water hygiene. In Europe, the only endemic *Vibrio* types are *V. cholerae* non-O1/non-O139 serogroups and other *Vibrio species*, collectively called non-cholera *Vibrio* (NCV). *V. cholerae* non-O1/non-O139 can lead to self-limiting infections with moderate diarrhoeal symptoms, but are rarely associated with food consumption. Gastrointestinal illness in Europe is mainly associated with haemolysin (*trh*/*tdh*)-encoding *V. parahaemolyticus* isolates and consumption of raw or undercooked seafood. *V. vulnificus*, on the other hand, plays an important role in severe wound infections, which is discussed in another article in this status report that looks more closely at effects of climate change on waterborne infections and intoxications (Dupke et al. [39]). This species is common in coastal waters of moderate salinity worldwide and has been associated with fatal infections from consumption of contaminated oysters, with mortality rates for primary septicaemia (blood poisoning) sometimes exceeding 50% [37]. Accurate information on foodborne *Vibrio* infections is not yet available, as pathogen detection in diarrhoeal diseases is often not part of risk-based diagnostics, and a mandatory notification requirement for human *Vibrio* infections does not exist throughout Europe. In Germany, only isolated cases of gastrointestinal NCV infections have been recorded since the introduction of mandatory notification according to the IfSG in 2020, which may indicate either low exposure to *Vibrio*-containing products or that a large proportion of the illnesses are not detected and thus not reported [40].

The importance of seafood has increased due to its high protein, vitamin and mineral content. For many years, the annual per capita consumption in Germany was covered

Environmentally associated germs such as waterborne *Vibrio* are increasingly finding their way into food, especially seafood, and causing an increase in infections.

by wild catch, but now increasingly comes from aquacultures. Usually, seafood is offered in processed form (e. g. heated, marinated, smoked) and should thus contain no or hardly any *Vibrio*. However, raw and insufficiently heated products pose a risk [40]. Mussels and oysters in particular are predestined to enrich even small amounts of *Vibrio* due to their way of filtering of nutrients from the water. Thus, they pose a health risk, especially for people with weakened immune systems or pre-existing conditions.

In mussels and oysters, *V. alginolyticus* (sometimes associated with middle ear infections in humans) and *V. parahaemolyticus* are frequently detected, and rarely *V. cholerae* non-O1/non-O139 and *V. vulnificus* have been reported, with *V. alginolyticus* occurring year-round and the other species occurring exclusively during the warm summer and fall months [41]. Within Europe, several countries (e. g. Spain, France, United Kingdom) cultivate mussels and oysters, some of which are heavily contaminated with toxigenic *Vibrio* (up to 25% toxigenic *V. parahaemolyticus*) [40].

There are hardly any reliable data available on the probability of occurrence of a health impairment after exposure to *Vibrio* species pathogenic to humans. In principle, the risk of health impairment correlates with the amount of ingested pathogenic *Vibrio* and is also dependent on the respective species. In addition, the probability of occurrence of a health impairment is increased in vulnerable groups of people (YOPI: young, old, pregnant, immunocompromised people).

Climate influence on *Vibrio* infections

Compared to the rest of the world, foodborne *Vibrio* infections have been rare in Europe so far, which may change in the future in the course of climate change. In general, water temperatures above 12°C and low or moderate salinity (1–25 g/L) have a favourable effect on the occurrence of *Vibrio* spp. [36]. Optimal growth conditions already occur in Europe during the summer months on the Atlantic coast and in inland seas [42]. The occurrence of *Vibrio* spp. is favoured by global warming and the increase of heatwaves and may lead to the spread of endemic *Vibrio* and possibly also to the establishment of new pathotypes in Europe, so that the human infection incidence may increase in the future, especially in coastal areas and estuaries [42, 43]. The continuous increase in water temperature will lead to an amplification of *Vibrio* contamination in European seafood catching, harvesting, and farming areas, and will also expand beyond the summer and autumn months. Currently, the occurrence of pathogenic *Vibrio* is low in bodies of water with fluctuating temperatures, such as the North Sea and the Baltic Sea, whereas toxigenic NCV are increasingly detected in waters with consistently warm temperatures, from which seafood is partly imported [41]. In seafood, the occurrence of species pathogenic to humans correlates directly with water temperatures as well [36, 40].

Minimisation of risk to humans, especially in relation to contact with and consumption of seafood, is possible by avoiding exposure to pathogenic species, e. g. through appropriate product processing strategies, thermal treatments, adherence to hygienic measures, a strict cold chain, and good and rapid monitoring immediately after capture, harvest, or import [40].

Rising temperatures and humidity favour fitness and possibly virulence of parasites such as *Cryptosporidium* and *Giardia*.

3. Parasites

Climate change can also influence infections by parasites, especially if these are characterised by a significant environmental presence and high environmental stability. This applies in particular to protozoa, unicellular organisms that live as parasites. Even if profound knowledge is lacking, recent research data (German Federal Institute for Risk Assessment (BfR); data not published) indicate that a changing climate also has a direct impact on the prevalence and virulence of these pathogens, which are already very stable in the environment. A risk of transmission to humans through food is usually associated with those foods that are consumed raw or inadequately cooked. Food contamination can occur via vectors (e.g. insects, mammals including those providing food to humans) but also via contaminated irrigation systems. In addition, food can be affected by cross-contamination, such as when hygiene is poor during food preparation.

3.1 Cryptosporidia

More than 40 different species of the protozoan genus *Cryptosporidium* have been described to date, which can infect a large number of different animal species and humans. Here, we focus on the species *Cryptosporidium (C.) parvum* and *C. hominis*, as they are responsible for the largest proportion of human infections [44]. *C. hominis* occurs almost exclusively in humans, while the primary hosts for *C. parvum* are cattle, horses, goats, and sheep, and, to a lesser extent, dogs, cats, and birds [45]. Infection occurs via the faecal-oral route by ingestion of the infective developmental stages (oocysts); transmissions from animal to animal, human to human, animal to human, and vice versa are possible [46]. However, infection can also occur through ingestion of contaminated water (e.g. swimming pool, river, lake, or spring water). Another source of infection can be plant-based foods that have been contaminated with infested water.

Cryptosporidiosis is one of the most common diarrhoeal diseases associated with the ingestion of contaminated water. In 2013, an outbreak with 167 cases was recorded in Germany in association with flooding after a heavy rain event [47]. Foodborne illnesses have also been described in Europe, which have been attributed to the consumption of lettuce [24].

In Germany, there is a mandatory notification requirement for detection of cryptosporidia in connection with an illness in accordance with the IfSG. Between 900 and 2,000 cases are reported to the RKI annually; in Europe, there are 8,000 to 14,000 cases annually. Data from the European Centre for Disease Prevention and Control (ECDC) show that cryptosporidiosis in Europe has seasonal increases in late spring and late summer to early autumn, respectively [48].

Young children, people with weakened immune systems, travellers to developing countries, and people who drink untreated water are at increased risk of infection.

Infection may be asymptomatic or symptomatic. Symptoms described include prolonged watery diarrhoea with weight loss, severe abdominal pain or cramps, nausea, vomiting, and headaches [49]. After infection, further complications (e.g. inflammation of the pancreas, appendicitis, impairment of the lungs) and even death may occur. After the

An increase in infections due to *Cryptosporidium* and *Giardia* is to be expected.

symptoms have subsided, the oocysts continue to be excreted in the stool for many weeks. The infectious dose of cryptosporidia is low, ranging from 10 to 1,000 oocysts, depending on the species [50]. However, it is suspected that one oocyst may be sufficient for infection in humans [51].

3.2 *Giardia*

Parasites of the protozoan genus *Giardia* can also be affected by climate change. *Giardia* are currently classified into eight species [52]. However, the species *Giardia (G.) duodenalis* (synonyms: *G. lamblia*, *G. intestinalis*) is the only species of this genus that can infect humans as well as numerous mammalian species. *G. duodenalis* is distributed worldwide; humans are considered the main reservoir. Infection occurs faecal-orally by ingestion of the infectious developmental stages of the parasite (1 to 10 cysts are sufficient) with contaminated tap water or untreated fresh water from lakes or streams. However, *Giardia* cysts can also be transmitted by eating contaminated food or by close contact with infected persons or animals [53].

Giardiasis caused by *G. duodenalis* is one of the most common intestinal parasitoses in humans worldwide [54]. Prevalence rates are significantly higher in developing countries than in developed countries. For example, 3,296 travel-associated cases of the disease were reported to the RKI in 2019; the most frequently cited country of infection was India [26]. However, as warming due to climate change continues, increased local infections will also be expected. Infants and young children, older persons, travellers, and immunocompromised persons are among the high-risk groups [55]. In more than 50% of cases, the disease is asymptomatic, but the course can be severe in infants and older persons [56].

In Germany, detection of this pathogen in connection with an illness is notifiable.

Globally, *G. duodenalis* is estimated to cause 28.2 million cases of diarrhoeal disease per year due to food contamination [52]. The European Food Safety Authority (EFSA) recorded 14 foodborne outbreaks and 3 outbreaks due to water consumption in Europe in 2019 [57]. Data on foodborne outbreaks in Germany are not yet available.

3.3 Climate influence on parasites

Cryptosporidium and *Giardia* can remain infectious for a long period of time and cause disease, especially after consumption of raw contaminated food.

Their high stability against environmental influences, in particular the long survivability in aqueous environments, suggests that these parasites could appear more frequently as pathogens in the future. Extreme weather such as heavy rainfall and flooding, which are also expected to increase in our latitudes as a result of climate change, increase the risk of infectious oocysts/cysts entering bodies of water, as well as the risk of contamination of plant-based foods. The risk for humans can be minimised by good kitchen hygiene.

4. Biogenic toxins of marine origin

More than 20% of the protein requirements of over 3 billion people worldwide are met by seafood. Consumption of fish as food has increased by 3.1% annually over the last 50 years [58]. Climate change is increasingly causing warm-

Ocean warming is leading to increased growth of toxin-producing algae, whose toxins can enter the food chain via marine animals.

ing, acidification, and oxygen depletion of the oceans, altered water salinity, and sea level rise. The temperature of the oceans' surface water has increased greatly, as more than 90% of the global temperature increase has been absorbed by the oceans [59]. These changes are affecting marine biodiversity, which in turn can significantly impact the availability of food, animal protein, and essential micronutrients for billions of people around the world [60, 61].

The above factors can also affect the abundance and composition of marine phytoplankton. Planktonic microalgae form the basis of the aquatic food web, but can have harmful effects if they occur in large abundance. The phenomenon of sudden, explosive growth of algae is called an algal bloom. When these algal blooms have negative consequences, such as creating hypoxic or anoxic conditions (lack of oxygen or complete absence of oxygen) or producing toxins, they are referred to as harmful algal blooms (HABs). HABs have the potential to disrupt fish communities and food webs, and can even lead to massive species extinctions [62]. Currently, approximately 300 microalgal species are known to be involved in the formation of such algal blooms. Of these, about 100 species can produce toxins that can lead to specific toxic syndromes in animals and humans.

Marine biotoxins enter the food chain through organisms that filter water or feed on algae, such as shellfish and fish, and thus may pose a threat to human health due to their toxic properties [63, 64]. Furthermore, exposure to toxins produced by marine phytoplankton can occur through inhalation or through the skin, via aerosols that contain toxins and cell fragments and can cause skin irritation and respiratory symptoms [65, 66].

Climate change is altering the geographic distribution of some algal species that may be involved in the formation of HABs. Warm-water species, for example, may be expanding poleward and appearing in areas where they were not previously native. In this context, identifying and studying the geographic distribution of toxin-producing organisms is critical for implementing appropriate preventive and control measures prior to harvest or during the distribution and sale of seafood. This is particularly important because marine biotoxins are not normally detectable by odour, taste, or appearance and are not usually destroyed by cooking, freezing, or other food preparation processes.

In the interests of preventive consumer health protection, maximum levels have been set within the EU for five different toxin groups in live bivalve molluscs. Furthermore, products containing compounds of the ciguatoxin group that can cause mild to severe poisoning (ciguatera) in humans [67] may not be marketed within the EU [68, 69].

5. Conclusion and recommendations

Climate change affects various habitats, which can be altered by weather events such as prolonged droughts, temperature increases, and heavy rains. These changes also affect the foods derived from these habitats and micro-organisms or toxins that may be associated with these foods. For example, foods may be more heavily contaminated with pathogens or contain germs that were not previously present in a region. But climate-related events also affect food indirectly. For example, ever-increasing water scarcity means more frequent use of treated wastewater for food irrigation. Because such wastewater may still contain parasites, bacteria, and viruses in disease-causing concentrations, plant parts that are commonly consumed raw should not come into contact with treated wastewater, or should continue to be irrigated with potable water [23–25]. Progressive climate change in Germany is expected to lead to an increase of the infections and intoxications discussed here, making them a growing public health concern.

Our main recommendations for minimising the health risk from foodborne infections and intoxications lie in the area of kitchen hygiene, which should always be applied when preparing food. This includes thorough hand washing and the use of fresh kitchen utensils after handling raw meat and fish, as well as avoidance of cross-contamination, i.e. direct or indirect pathogen transmission from one food to another. Wearing gloves can prevent the entry of pathogens via unnoticed skin lesions. Food safety is also highly dependent on maintaining the cold chain. In addition, most microbiological pathogens can be safely killed by a sufficient heating process; for example, a core temperature of 70°C for at least two minutes must be maintained when preparing seafood. In contrast, biogenic toxins associated with food are largely insensitive to temperature [40, 70, 71].

We also recommend the use of new technologies to track supply chains. Given a globalised food distribution network and the use of different processing and preservation techniques, it can be difficult to track a product's supply chain to identify potential risks. Technological advances have produced digital solutions for this; knowledge of fish stocks, seafood traceability and supply chain transparency can benefit from innovative approaches. These include blockchain or radio frequency identification device tags for product authentication (including species and catch data), as well as applications of machine learning, data mining, artificial intelligence, and other digital technologies [72]. These methods of digitally-enabled food supply chains can support sustainable development in the food industry, which aims to reward responsible and ethical producers and keep illegal or unethically produced food products out of supply chains [73].

Further research is needed on the links between climatic changes and disease incidence, and on the geographic distribution of toxin-producing organisms.

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Authors' contributions

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All authors have made comparable contributions.

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References

1. Mora C, McKenzie T, Gaw IM et al. (2022) Over half of known human pathogenic diseases can be aggravated by climate change. Nat Clim Chang 12(9):869–875
2. Thebo AL, Drechsel P, Lambin EF et al. (2017) A global, spatially-explicit assessment of irrigated croplands influenced by urban wastewater flows. Environ Res Lett 12(7):074008
3. Beermann S, Dobler G, Faber M et al. (2023) Impact of climate change on vector- and rodent-borne infectious diseases. J Health Monit 8(S3):33–61. www.rki.de/jhealthmonit-en (As at 01.06.2023)
4. Wingstrand A, Neimann J, Engberg J et al. (2006) Fresh chicken as main risk factor for campylobacteriosis, Denmark. Emerg Infect Dis 12(2):280–285
5. European Food Safety Authority (2010) Scientific opinion on quantification of the risk posed by broiler meat to human campylobacteriosis in the EU. EFSA Journal 8(1):1437
6. Rosner BM, Schielke A, Didelot X et al. (2017) A combined case-control and molecular source attribution study of human *Campylobacter* infections in Germany, 2011–2014. Sci Rep 7(1):5139
7. Stingl K, Knuver MT, Vogt P et al. (2012) Quo vadis? – Monitoring *Campylobacter* in Germany. Eur J Microbiol Immunol (Bp) 2(1):88–96
8. Schonberg-Norio D, Takkinen J, Hanninen ML et al. (2004) Swimming and *Campylobacter* infections. Emerg Infect Dis 10(8):1474–1477
9. Hyllestad S, Iversen A, MacDonald E et al. (2020) Large water-borne *Campylobacter* outbreak: Use of multiple approaches to investigate contamination of the drinking water supply system, Norway, June 2019. Euro Surveill 25(35):2000011
10. Patrick ME, Christiansen LE, Waino M et al. (2004) Effects of climate on incidence of *Campylobacter* spp. in humans and prevalence in broiler flocks in Denmark. Appl Environ Microbiol 70(12):7474–7480
11. Ishihara K, Takahashi R, Andoh M et al. (2012) Effects of climatic elements on *Campylobacter*-contaminated chicken products in Japan. Epidemiol Infect 140(6):991–996

12. Williams MS, Golden NJ, Ebel ED et al. (2015) Temporal patterns of *Campylobacter* contamination on chicken and their relationship to campylobacteriosis cases in the United States. Int J Food Microbiol 208:114–121

13. Meldrum RJ, Griffiths JK, Smith RM et al. (2005) The seasonality of human *Campylobacter* infection and *Campylobacter* isolates from fresh, retail chicken in Wales. Epidemiol Infect 133(1):49–52

14. David JM, Pollari F, Pintar KD et al. (2017) Do contamination of and exposure to chicken meat and water drive the temporal dynamics of *Campylobacter* cases? Epidemiol Infect 145(15):3191–3203

15. Rushton SP, Sanderson RA, Diggle PJ et al. (2019) Climate, human behaviour or environment: Individual-based modelling of *Campylobacter* seasonality and strategies to reduce disease burden. J Transl Med 17(1):34

16. Louis VR, Gillespie IA, O'Brien SJ et al. (2005) Temperature-driven *Campylobacter* seasonality in England and Wales. Appl Environ Microbiol 71(1):85–92

17. Oberheim J, Hoser C, Luchters G et al. (2020) Small-scaled association between ambient temperature and campylobacteriosis incidence in Germany. Sci Rep 10(1):17191

18. Soneja S, Jiang C, Romeo Upperman C et al. (2016) Extreme precipitation events and increased risk of campylobacteriosis in Maryland, U.S.A. Environ Res 149:216–221

19. Kuhn KG, Nygard KM, Guzman-Herrador B et al. (2020) *Campylobacter* infections expected to increase due to climate change in Northern Europe. Sci Rep 10(1):13874

20. Sterk A, Schijven J, de Roda Husman AM et al. (2016) Effect of climate change on runoff of *Campylobacter* and *Cryptosporidium* from land to surface water. Water Res 95:90–102

21. Duchenne-Moutien RA, Neetoo H (2021) Climate change and emerging food safety issues: A Review. J Food Prot 84(11):1884–1897

22. Umweltbundesamt (2021) Neue EU-Verordnung zu Wasserwiederverwendung.
https://www.umweltbundesamt.de/themen/wasser/wasserbewirtschaften/wasserwiederverwendung/neue-eu-verordnung-zu-wasserwiederverwendung (As at 15.01.2023)

23. Bundesinstitut für Risikobewertung (BfR) (2020) Reclaimed waste water: Preventing bacterial pathogens on fresh fruit and vegetables.
https://www.bfr.bund.de/cm/349/reclaimed-waste-water-preventing-bacterial-pathogens-on-fresh-fruit-and-vegetables.pdf (As at 23.01.2023)

24. BfR (2022) Reclaimed waste water: Preventing protozoa on plant foods.
https://www.bfr.bund.de/cm/349/reclaimed-wastewater-preventing-protozoa-on-plant-foods.pdf (As at 23.01.2023)

25. BfR (2022) Reclaimed waste water: Preventing viral pathogens on plant foods.
https://zenodo.org/record/7346234 (As at 12.05.2023)

26. Falkenhorst G, Enkelmann J, Frank C et al. (2020) Zur Situation bei wichtigen Infektionskrankheiten – Reiseassoziierte Krankheiten 2019. Epid Bull 50:7–20

27. Interagency Food Safety Analytics Collaboration (2021) Foodborne illness source attribution estimates for 2019 for *Salmonella*, *Escherichia coli* O157, *Listeria monocytogenes* and *Campylobacter* using multi-year outbreak surveillance data, United States. Department of Health and Human Services' Centers for Disease Control and Prevention and U.S. Food and Drug Administration; U.S. Department of Agriculture's Food Safety and Inspection Service.
https://www.cdc.gov/foodsafety/ifsac/pdf/P19-2019-report-TriAgency-508.pdf (As at 15.01.2023)

28. EFSA, ECDC (2021) The European Union One Health 2020 zoonoses report. EFSA Journal 19(12):6971

29. Olaimat AN, Holley RA (2012) Factors influencing the microbial safety of fresh produce: A review. Food Microbiol 32(1):1–19

30. Beuchat LR (2002) Ecological factors influencing survival and growth of human pathogens on raw fruits and vegetables. Microbes Infect 4(4):413–423

31. Zhang Y, Bi P, Hiller JE (2010) Climate variations and *Salmonella* infection in Australian subtropical and tropical regions. Sci Total Environ 408(3):524–530

32. Akil L, Ahmad HA, Reddy RS (2014) Effects of climate change on *Salmonella* infections. Foodborne Pathog Dis 11(12):974–980

33. Zhang Y, Bi P, Hiller J (2008) Climate variations and salmonellosis transmission in Adelaide, South Australia: A comparison between regression models. Int J Biometeorol 52(3):179–187

34. Butsch C, Beckers LM, Nilson E et al. (forthcoming) Health impacts of extreme weather events – Cascading risks in a changing climate. J Health Monit. www.rki.de/jhealthmonit-en

35. Farmer III, JJ, Janda JM, Brenner FW et al. (2015) Vibrio. In: Whitman WB (Ed) Bergey's manual of systematics of archaea and bacteria. John Wiley & Sons, Inc., in association with Bergey's Manual Trust, P. 1–79

36. Food and Agriculture Organization of the United Nations (FAO), WHO (2020) Risk assessment tools for *Vibrio parahaemolyticus* and *Vibrio vulnificus* associated with seafood. Microbiological risk assessment series;20. Rome. https://apps.who.int/iris/handle/10665/330867 (As at 15.01.2023)

37. Centers for Disease Control and Prevention (2019) *Vibrio* and food. https://www.cdc.gov/vibrio/food.html (As at 15.01.2023)

38. DSMZ (2022) LPSN - List of Prokaryotic names with Standing in Nomenclature. Genus *Vibrio*. https://lpsn.dsmz.de/genus/vibrio (As at 15.01.2023)

39. Dupke S, Buchholz U, Fastner J et al. (2023) Impact of climate change on waterborne infections and intoxications. J Health Monit 8(S3): 62–77. www.rki.de/jhealthmonit-en (As at 01.06.2023)

40. BfR (2022) Bacterial foodborne Vibrio infections: Health risk assessment of the occurrence of *Vibrio* spp. (non-cholera vibrios) in food. https://www.bfr.bund.de/cm/349/bacterial-foodborne-vibrio-infections-health-risk-assessment-of-the-occurrence-of-vibrio-spp-in-food.pdf (As at 23.01.2023)

41. Martinez-Urtaza J, Bowers JC, Trinanes J et al. (2010) Climate anomalies and the increasing risk of *Vibrio parahaemolyticus* and *Vibrio vulnificus* illnesses. Food Res Int 43(7):1780–1790

42. Baker-Austin C, Oliver JD, Alam M et al. (2018) *Vibrio* spp. infections. Nat Rev Dis Primers 4(1):8

43. Vezzulli L, Baker-Austin C, Kirschner A et al. (2020) Global emergence of environmental non-O1/O139 *Vibrio cholerae* infections linked with climate change: A neglected research field? Environ Microbiol 22(10):4342–4355

44. O'Leary JK, Blake L, Corcoran GD et al. (2021) Development of a novel, high resolution melting analysis based genotyping method for *Cryptosporidium parvum*. Eur J Protistol 79:125799

45. Bouzid M, Hunter PR, Chalmers RM et al. (2013) *Cryptosporidium* pathogenicity and virulence. Clin Microbiol Rev 26(1):115–134

46. Davies AP, Chalmers RM (2009) Cryptosporidiosis. BMJ 339:b4168

47. Gertler M, Durr M, Renner P et al. (2015) Outbreak of *Cryptosporidium hominis* following river flooding in the city of Halle (Saale), Germany, August 2013. BMC Infect Dis 15:88

48. Caccio SM, Chalmers RM (2016) Human cryptosporidiosis in Europe. Clin Microbiol Infect 22(6):471–480

49. Carter BL, Chalmers RM, Davies AP (2020) Health sequelae of human cryptosporidiosis in industrialised countries: A systematic review. Parasit Vectors 13(1):443

50. RKI (2004) RKI-Ratgeber Infektionskrankheiten – Merkblätter für Ärzte. Kryptosporidiose. Epid Bull 34:279–281

51. Hamilton KA, Waso M, Reyneke B et al. (2018) *Cryptosporidium* and *Giardia* in wastewater and surface water environments. J Environ Qual 47(5):1006–1023

52. Ryan U, Hijjawi N, Feng Y et al. (2019) *Giardia*: An underreported foodborne parasite. Int J Parasitol 49(1):1–11

53. Burnett MW (2018) Giardiasis. J Spec Oper Med 18(1):106–107

54. Certad G, Viscogliosi E, Chabe M et al. (2017) Pathogenic mechanisms of *Cryptosporidium* and *Giardia*. Trends Parasitol 33(7):561–576

55. Leung AKC, Leung AAM, Wong AHC et al. (2019) Giardiasis: An overview. Recent Pat Inflamm Allergy Drug Discov 13(2):134–143

56. Rumsey P, Waseem M (2021) Giardia Lamblia Enteritis. In: StatPearls. StatPearls Publishing, Treasure Island (FL)

57. EFSA, ECDC (2021) The European Union One Health 2019 zoonoses report. EFSA Journal 19(2):6406

58. FAO (2020) The state of world fisheries and aquaculture 2020. Sustainability in action. Rome. https://www.fao.org/documents/card/en/c/ca9229en/ (As at 15.01.2023)

59. IPCC (2019) Summary for Policymakers. In: Pörtner HO, Roberts DC, Masson-Delmotte V et al. (Eds) Intergovernmental Panel on Climate Change special report on the ocean and cryosphere in a changing climate. Cambridge University Press, Cambridge, UK und New York, NY, USA, P. 3–35. https://www.cambridge.org/core/services/aop-cambridge-core/content/view/097A895553D86981DFE6195ADFD3DDA4/stamped-9781009157971pre2_3-36.pdf/summary_for_policymakers.pdf (As at 16.01.2023)

60. Hicks CC, Cohen PJ, Graham NAJ et al. (2019) Harnessing global fisheries to tackle micronutrient deficiencies. Nature 574(7776):95–98

61. Falkenberg LJ, Bellerby RGJ, Connell SD et al. (2020) Ocean acidification and human health. Int J Environ Res Public Health 17(12):4563

62. Kudela RM, Berdalet E, Bernard S et al. (2015) Harmful algal blooms: A scientific summary for policy makers. Intergovernmental Oceanographic Commission, Scientific Committee on Oceanic Research, Paris. https://unesdoc.unesco.org/ark:/48223/pf0000233419 (As at 15.01.2023)

63. Friedman MA, Fernandez M, Backer LC et al. (2017) An updated review of ciguatera fish poisoning: Clinical, epidemiological, environmental, and public health management. Mar Drugs 15(3):72

64. Food and Drug Administration (2020) Fish and fishery products hazards and controls guidance. Fourth Edition U.S. Food Drug Administration. https://www.fda.gov/media/80637/download (As at 15.01.2023)

65. Ciminiello P, Dell'Aversano C, Iacovo ED et al. (2014) First finding of *Ostreopsis* cf. *ovata* toxins in marine aerosols. Environ Sci Technol 48(6):3532–3540

66. Pierce R, Henry M, Blum P et al. (2003) Brevetoxin concentrations in marine aerosol: Human exposure levels during a *Karenia brevis* harmful algal bloom. Bull Environ Contam Toxicol 70(1):161

67. FAO, WHO (2020) Report of the expert meeting on ciguatera poisoning: Rome, 19–23 November 2018. Food safety and quality series; 9. Rome. https://apps.who.int/iris/handle/10665/332640 (As at 15.01.2023)

68. EFSA Panel on Contaminants in the Food Chain (2010) Scientific opinion on marine biotoxins in shellfish – Emerging toxins: Ciguatoxin group. EFSA Journal 8(6):1627

69. Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004 laying down specific hygiene rules for food of animal origin. Official Journal of the European Union L 139/55, Vol 47. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32004R0853R(01)&from=EN (As at 16.01.2023)

70. BfR (2018) Game meat: Health assessment of human-pathogenic parasites. https://www.bfr.bund.de/cm/349/game-meat-health-assessment-of-human-pathogenic-parasites.pdf (As at 23.01.2023)

71. BfR (2019) Schutz vor lebensmittelbedingten Infektionen mit *Campylobacter*. https://www.bfr.bund.de/cm/350/verbrauchertipps-schutz-vor-lebensmittelbedingten-infektionen-mit-campylobacter.pdf (As at 15.01.2023)

72. Loeffler CR, Tartaglione L, Friedemann M et al. (2021) Ciguatera mini review: 21st century environmental challenges and the interdisciplinary research efforts rising to meet them. Int J Environ Res Public Health 18(6):3027

73. Tsolakis N, Niedenzu D, Simonetto M et al. (2020) Supply network design to address United Nations Sustainable Development Goals: A case study of blockchain implementation in Thai fish industry. J Bus Res 131:495–519

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Antimicrobial resistance in Germany and Europe – A systematic review on the increasing threat accelerated by climate change

Abstract

Background: Antimicrobial Resistance (AMR) is one of the top ten global public health threats facing humanity, alongside climate change. Here, we aim to summarise the effects of climate change (i.e. raise of temperature, change in humidity or precipitation) on spread of antibiotic resistance and on infections with antibiotic-resistant bacteria in Germany.

Methods: We conducted a literature search with articles published between January 2012 and July 2022. Two authors screened titles, abstracts and full texts and extracted the data systematically.

Results: From originally 2,389 titles, we identified six studies, which met our inclusion criteria. These studies show that an increase in temperature may lead to higher antibiotic resistance rates and an increased risk of colonisation as well as spread of pathogens. Furthermore, the number of healthcare-associated infections increases with increased temperature. Data indicate that higher antibiotic use is present in areas with warmer mean temperature.

Conclusions: European data are scarce, but all studies identified point towards an increasing AMR burden due to climate change. However, further studies are needed to draw attention to the links between climatic factors and AMR and develop targeted preventive measures.

This is part of a series of articles that constitute the German Status Report on Climate Change and Health 2023.

CLIMATE CHANGE · ANTIMICROBIAL RESISTANCE AND CONSUMPTION · HEALTHCARE-ASSOCIATED INFECTIONS

1. Introduction

Climate change has a clear impact on disease burden globally, and there is sufficient evidence to act now to mitigate the climate crisis. However, it remains challenging to quantify the impact of climate change on health for many diseases. The complexity of climate-dependent modifying factors of infectious diseases challenges the precision of modelling pathways and subsequent impacts.

Since the availability of antimicrobials, infections due to bacteria, viruses, fungi and parasites have become treatable. However, due to the misuse and overuse of antimicrobials, these pathogens become increasingly resistant. In 2019, the World Health Organization (WHO) declared antimicrobial resistance (AMR) one of the top ten global public health threats facing humanity, alongside climate change [1, 2]. According to a recent study on the global burden of AMR, an estimated 4.95 million deaths were

Climate change and AMR are two of the biggest and most complex threats facing the world. Both have been exacerbated by, but can be contained through, human action.

associated with bacterial AMR (i.e. deaths due to infection with antimicrobial-resistant bacteria for which AMR may/may not be the cause) in 2019. Attributable deaths to bacterial AMR (i.e. deaths due to untreatable AMR infection, caused by drug resistance) accounted for 1.27 million deaths [3]. In European countries, Cassini et al. [4] estimated the burden of infections with antibiotic-resistant bacteria in 2015 and identified four antibiotic-resistant bacteria with the largest effect on human health: third-generation cephalosporin-resistant *Escherichia coli* (*E. coli*), meticillin-resistant *Staphylococcus aureus* (*S. aureus*), carbapenem-resistant *Pseudomonas aeruginosa* (*P. aeruginosa*) and third-generation cephalosporin-resistant *Klebsiella pneumoniae* (*K. pneumoniae*). These findings were recently confirmed by Mestrovic et al. [5] in another European systematic analysis in 2019, which highlighted regional differences in AMR burden, showing that the burden of AMR is higher in countries in the Mediterranean region, like Greece or Italy, compared to countries in the Northern European region, which could be linked to differences in climate among other factors [4]. Furthermore, the Organisation for Economic Co-operation and Development (OECD) estimated that 75% of the AMR burden derives from healthcare-associated infections (HAIs) [6].

Temperature, which may increase due to climate change [7], is known to have an effect on bacterial growth and reproduction; the optimal growth temperature for many key bacteria is above 30°C [8]. There is some evidence that plasmid transfer and potentially gene transfer of resistance genes are facilitated by increased temperature [9]. Hints for the relationship between climatic factors such as temperature and AMR have also been recently found. For example, MacFadden et al. [10] found that AMR in common pathogens such as *S. aureus*, *E. coli* and *K. pneumoniae* increased with increasing temperature.

In this review, we aim to summarise the key effects that climate change may have on the spread and burden of AMR among humans in Germany and Europe. We conducted a literature review and adapted a graphical model to support this assessment.

2. Methods

We conducted a literature search limited to peer reviewed articles published between January 2012 and July 2022 in English, French or German. PubMed was searched using the keywords climate change, temperature, healthcare-associated infection (HAI), and antimicrobial resistance, including the MeSH terms for climate change, global warming, climatic processes, antibacterial agents, and drug resistance (bacterial). The complete search string is documented in the Annex. Further literature was retrieved from citation screening of selected articles. Studies were restricted to those including countries of the European Union (EU) and/or European Economic Area (EEA) and to primary analyses or reviews (e.g. editorials were excluded) for this review. This review considers the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement [11].

Two authors (AM and FW) independently of each other screened titles, abstracts and full texts and extracted the following data systematically: citation, study period, study design, demographics, climate indicators, definition of outcome as pathogen and/or antimicrobial resistance and/or infections analysed. Discrepancies between the reviewers were solved by discussion until a consensus was reached. Data were summarised in tables and stratified by drug resistance, pathogen and type of infection.

Additionally, we utilised the webtool provided by Mora et al. [12] to further illustrate the impact of climate change on AMR pathogens. Based on a comprehensive global review of available literature and collected data, the tool allows the user to model pathways in which climatic hazards, through different transmission routes, impact specific diseases. The authors comprehensively assessed the evidence from climatic hazards worldwide. We adapted the model using this tool by concentrating on the main AMR pathogens responsible for the European AMR burden highlighted by Cassini et al. [4].

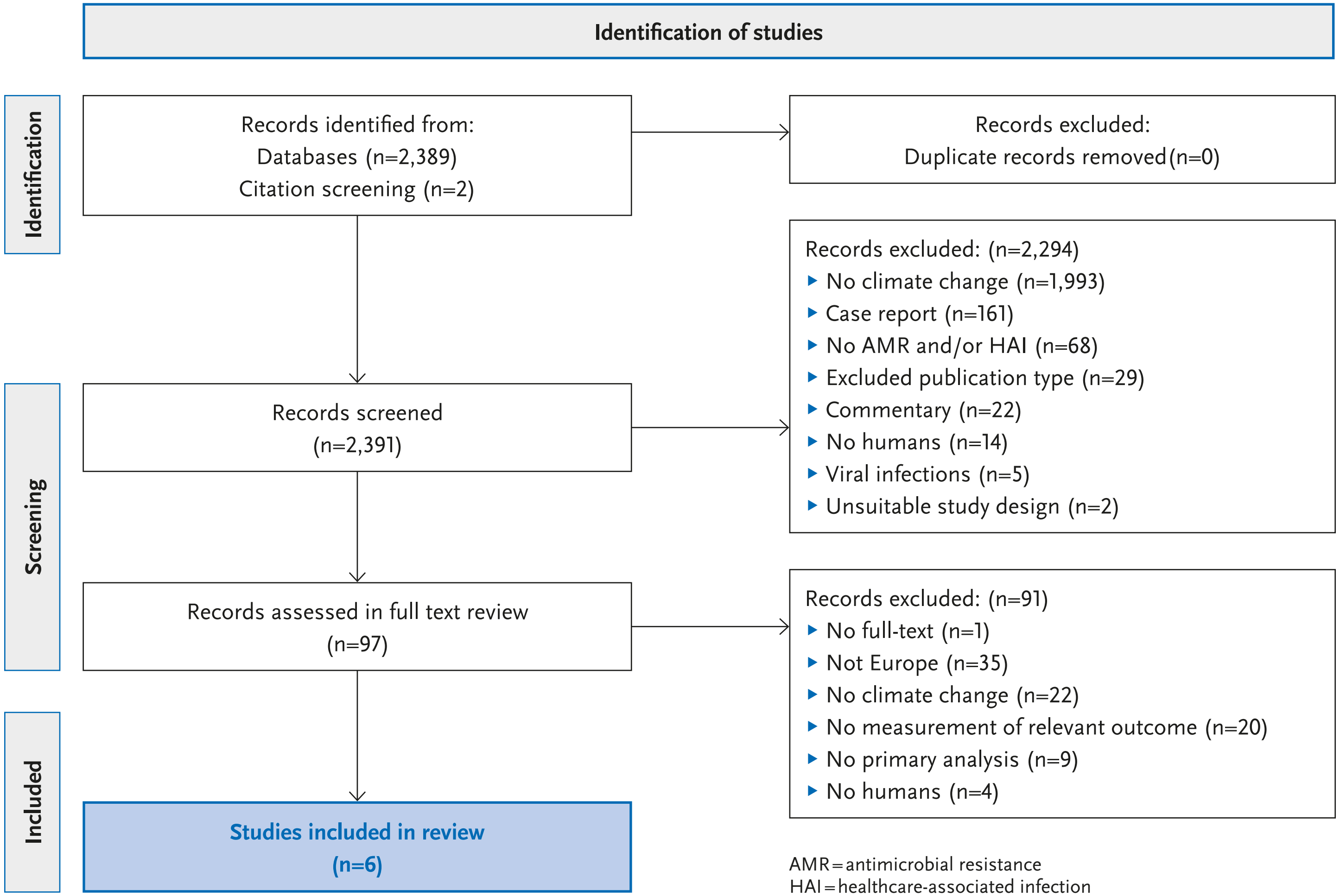
3. Results

Our search identified a total of 2,389 titles (Figure 1). After eliminating duplicates and screening the remaining titles and abstracts, 97 publications were left for full text evaluation. Of these, only six studies met our selection criteria (Table 1). Due to our focus on the situation in Germany and EU/EEA countries, we excluded the non-European studies for this summary (n=35). Most eligible studies were observational studies.

3.1 Body of evidence for association of increases in temperature and occurrence of AMR

Using data from the European Antimicrobial Resistance Surveillance Network (EARS-Net), McGough et al. [14] showed that AMR in *E. coli* and *K. pneumoniae* increased from 2000 to 2016, whereas meticillin-resistant *S. aureus* (MRSA) decreased over time. The reduction of MRSA detection is commonly attributed to targeted public action and, thus, may not be explained by climate indicators [19]. Kaba et al. [13] and McGough et al. [14] show a correlation between warmer temperature (whether expressed as mean temperature or as minimum ambient temperature) and an increase in antibiotic resistance. Warm season mean temperature was identified as a predictor for MRSA, multi-drug-resistant *E. coli* (MREC) and carbapenem-resistant *K. pneumoniae* (CRKP). With increases in mean temperature, the rates of MRSA, MREC and CRKP were shown to increase [13]. Furthermore, McGough et al. [14] demonstrated that AMR increases faster at higher temperatures. In warmer countries, where mean temperature is 10°C higher than the overall mean temperature in European countries, an increased rate of change of AMR by 0.33% per year for aminoglycoside-resistant *E. coli* and 0.55% per year for third-generation cephalosporin-resistant *E. coli* was observed. For fluoroquinolone-resistant *E. coli,* an increase of 0.57% per year was found after accounting for other recognised resistance drivers including antibiotic consumption and population density. For *K. pneumoniae,* even higher increases were identified: 0.9% per year for third-generation cephalosporin-resistant *K. pneumoniae* and 1.2% for fluoroquinolone-resistant *K. pneumoniae*. McGough et al. [14] concluded that ambient temperature might considerably influence antibiotic resistance growth rates. In a review, Forrester et al. [15] also concluded that temperature increase due to climate change causes an increase in resistance in pathogenic bacteria.

Figure 1
Depiction of literature selection adapted from the PRISMA Flow Diagram [11]



AMR = antimicrobial resistance
HAI = healthcare-associated infection

3.2 Body of evidence for association of increases in temperature and humidity with bacterial pathogen growth and spread

The optimal growth temperature for many relevant bacteria is above 30°C [8], so increased bacterial proliferation with increasing temperatures seems likely. In their review, Forrester et al. [15] state that higher temperatures and humidity increase colonisation and infection risk of MRSA. Seasonality was also reported to affect colonisation or infection with *Clostridioides difficile*, varying by the Southern and Northern hemisphere. Although they found no data

Table 1
Information on the six studies that met inclusion criteria of this review. Studies are sorted by author, measured exposure (climate factors), outcome (AMR and/or infection), and results are displayed.

First author and publication year	Observational period	Country	Data source	Study design	Exposure measurement	Outcome measurement	Results
Kaba [13], **2020**	2011–2016	30 countries (all EU and EEA members, in addition to Iceland and Norway)	EARS-Net Surveillance data (routine AST results are collected from clinical laboratories by the national network); historical temperature data	Observational ecological study	Historical monthly mean temperature	Annual national AMR prevalence (CRPA, CRKP, MREC, MRSA)	Significant correlation between warm season (May–October) mean temperature and MRSA (Rs=0.826), MREC (Rs=0.718) and CRKP (Rs=0.798); correlation between cold season (November–April) mean temperature and MRSA (Rs=0.691); correlation with warm season net change in temperature and CRPA (Rs=0.748) and MREC (Rs=0.617); **warm season mean temperature is a significant predictor of MRSA, MREC and CRKP, but not CRPA**
McGough [14], **2020**	2000–2016	28 European countries (all EU and EEA members in addition to Iceland, Norway and United Kingdom)	EARS-Net Surveillance data (routine AST results are collected from clinical laboratories by the national network); modelled and assimilated meteorological data, available at Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2)	Observational ecological study	Annual minimum ambient temperature	Annual national AMR prevalence (aminopenicillins (*E. coli*), third-generation cephalosporins (*E. coli and K. pneumoniae*), fluoroquinolones (*E. coli and K. pneumoniae*), aminoglycosides (*E. coli and K. pneumoniae*), and meticillin (*S. aureus*))	AMR in *E. coli* & *K. pneumoniae* increased over time for most European countries, MRSA generally decreased over time; positive linear association between minimum ambient temperature and AMR across all countries, years, pathogens, and antibiotic subclasses; **relationship between temperature and resistance increases with time and AMR increases faster at higher temperatures**
Forrester [15], **2022**	1990–2020	22 countries: 15 European countries, 7 low- and middle income countries	101 publications	Review	Temperature, humidity, seasons	Infection or colonisation with common antibiotic-resistant or antibiotic-associated pathogens (MRSA, *C. difficile*, CRE)	MRSA: **higher temperatures and humidity** have been documented to increase colonisation and infection **with MRSA**; *C. difficile*: **Seasonality** has been reported to **affect colonisation or infection with *C. difficile*** and varies by Southern (October–November) and Northern Hemisphere (March–April)

AMR=antimicrobial resistance, AOR=adjusted odds ratio, AST=antimicrobial susceptibility testing, *C. albicans*=*Candida albicans*, *C. difficile*=*Clostridioides difficile* CI=confidence interval, CRE=carbapenem-resistant Enterobacteriaceae, CRKP=carbapenem-resistant *K. pneumoniae*, CRPA=carbapenem-resistant *P.aeruginosa*, DWD=Deutscher Wetterdienst (German Meteorological Service), EARS-Net=European Antimicrobial Resistance Surveillance Network, EEA=European Economic Area, EU=European Union, ha-BSI=healthcare-associated bloodstream infection, ICU=intensive care unit, IRR=incidence rate ratio, KISS=Krankenhaus-Infektions-Surveillance-System (German Nosocomial Infection Surveillance System), MRSA=meticillin-resistant *S. aureus*, MREC=multi-drug-resistant *E. coli*, Rs=Spearman rank correlation coefficient, SSI=surgical site infection, *S. pneumoniae*=*Streptococcus pneumoniae*
*Both articles used the same data set and should be considered together.

Continued on next page

First author and publication year	Observational period	Country	Data source	Study design	Exposure measurement	Outcome measurement	Results
Aghdassi [16]*, **2019**	2000–2016	Germany	Surgical procedures and SSI from KISS; meteorological monitoring station data of DWD	Observational ecological study	Monthly mean temperature	Rates of SSIs per 1,000 surgeries	Number of SSIs per 1,000 surgeries increased with higher temperatures; **SSI at temperatures ≥20°C more likely compared to temperatures <5°C (AOR: 1.13 [95% CI: 1.06–1.20])**; occurrence of superficial SSI with gram-negative pathogens up to 38% more likely with temperatures ≥20°C (AOR: 1.38 [95% CI: 1.16–1.64]) compared to temperatures <5°C; number of SSIs per 1,000 surgeries increased by 1% per 1°C increase
Schwab [17], **2020**	2001–2015	Germany	SSIs from ICUs participating in 'ICU-KISS' module of KISS; climate station network data of DWD	Observational ecological study	Daily mean temperature, daily maximum temperature, daily precipitation, relative humidity, and the daily duration of sunshine	Incidence of primary healthcare-associated bloodstream infections (ha-BSIs) stratified by pathogens per 10,000 patient days	**Incidence of ha-BSIs 17% (IRR 1.169 [95% CI: 1.077-1.269]) higher in months >20˚C compared to months <5˚C**; this effect is one third (38%) higher for gram-negative pathogens and 13% higher for gram-positive pathogens; *S. pneumoniae* occurred 50% less frequently at months >20°C than at <5°C.
Aghdassi [18]*, **2021**	2000–2016	Germany	Surgical procedures and SSI from 'OP-KISS' module of KISS, data from DWD	Observational ecological study	Monthly mean temperature	Rates of surgical site infections (SSIs) per 1,000 operations stratified by pathogens (*S. aureus*, *Enterococcus* spp., coagulase-negative staphylococci, *Streptococcus* spp., *Corynebacterium* spp., *E. coli*, *P. aeruginosa*, *Enterobacter* spp., *Klebsiella* spp., *Proteus* spp., *Bacteroides* spp., *Citrobacter* spp., other Enterobacteriaceae, *Serratia* spp., *Acinetobacter* spp., *C. albicans*)	**Correlation between higher temperatures and occurrence of SSIs; increase in SSI rate per additional 1°C for almost all pathogens excluding *Streptococcus* spp. and *C. albicans*;** strongest association for risk for SSIs with *Acinetobacter* spp. (6% increase per additional 1°C) and *Enterobacter* spp. (4% increase per additional 1°C); risk for SSIs caused by *Acinetobacter* spp. and *Enterobacter* spp. increased >2-fold in months with ≥20°C compared to <5°C

AMR = antimicrobial resistance, AOR = adjusted odds ratio, AST = antimicrobial susceptibility testing, *C. albicans*=*Candida albicans*, *C. difficile*=*Clostridioides difficile* CI = confidence interval, CRE = carbapenem-resistant Enterobacteriaceae, CRKP = carbapenem-resistant *K. pneumoniae*, CRPA = carbapenem-resistant *P.aeruginosa*, DWD = Deutscher Wetterdienst (German Meteorological Service), EARS-Net=European Antimicrobial Resistance Surveillance Network, EEA = European Economic Area, EU = European Union, ha-BSI = healthcare-associated bloodstream infection, ICU = intensive care unit, IRR = incidence rate ratio, KISS = Krankenhaus-Infektions-Surveillance-System (German Nosocomial Infection Surveillance System), MRSA = meticillin-resistant *S. aureus*, MREC = multi-drug-resistant *E. coli*, Rs=Spearman rank correlation coefficient, SSI = surgical site infection, *S. pneumoniae*=*Streptococcus pneumoniae*
*Both articles used the same data set and should be considered together.

Increases in temperature and changes in humidity and precipitation may increase the spread of AMR and healthcare-associated infections.

supporting associations of temperature, humidity or seasonality with carbapenem-resistant Enterobacteriaceae (CRE), they hypothesised that such associations could also be plausible [15]. Surveillance studies by Aghdassi et al. [16, 18] and Schwab et al. [17] suggested that changes in the microbiome composition could potentially be modified by rising temperatures. Thus, bacterial pathogen growth and spread may be facilitated by increased temperatures, even though the mechanisms underlying the hypothesis that to a certain extent higher temperatures lead to more bacterial proliferation are not fully understood.

3.3 Body of evidence for association of increases in temperature and humidity with healthcare-associated infections

There is also evidence that the number of HAIs increases with increased temperature. This is of relevance because 75% of the AMR burden stem from HAIs, which result in higher use of antibiotics [6]. Surgical site infections (SSIs) belong to the most common HAIs with an estimated 800,000 cases per year in the EU. Most frequently found pathogens in SSIs are *S. aureus*, *Enterococcus* spp. and *E. coli* [18]. In particular, Aghdassi et al. [16] showed that SSIs occur more often after surgeries in warmer months (≥20°C) compared to months with colder temperatures (<5°C) (adjusted Odds Ratio (AOR): 1.13, 95% confidence interval (CI): 1.06–1.20). SSIs increased when temperatures rose above 20°C during the month of surgery with both gram-negative and gram-positive pathogens. When considering temperature as a continuous variable, data showed that the likelihood of SSI occurrence increases by 1% per 1°C increase in temperature. Stronger associations between warmer temperatures and an increase in SSIs can be found in gram-negative pathogens. Furthermore, superficial SSIs appeared to have a higher temperature-related association than deeper SSIs. Superficial SSIs with gram-negative pathogens occurred 38% more frequently while temperatures were ≥20°C, compared to months with temperatures <5°C [16]. In a second study, Aghdassi et al. [18] found an increased risk of 6% for SSI with *Acinetobacter baumannii* per 1°C increase and a 4% risk for SSI with *Enterobacter* spp. in Germany. There was no association found between risk of SSI with *Streptococcus* spp. or *Candida albicans* and an increase in temperature.

Another study by Schwab et al. [17] reported on healthcare-associated primary bloodstream infections (ha-BSIs) in intensive care units (ICUs) and identified an association between the increase in mean daily temperature and ha-BSIs. In months with temperatures ≥20°C, the incidence rate of ha-BSIs was 17% higher than in months with temperatures <5°C. The effect of temperature is most prominent for ha-BSIs with gram-negative pathogens (38% incidence rate increase), followed by ha-BSIs with gram-positive pathogens (13% incidence rate increase). The only exception was found in *Streptococcus pneumoniae* with a reduced incidence rate ratio (IRR) of 0.498 (95% CI: 0.174–1.429) for temperatures ≥20°C compared to temperatures <5°C. This may well be explained by its transmission pathway via droplets, which is more relevant when the population stays predominantly indoors during colder seasons. In addition to temperature, relative humidity inversely correlated with an increase in ha-BSIs [17].

Climate change contributing to more frequent and severe extreme weather events will likely result in increased antimicrobial drug use in humans and animals.

3.4 Body of evidence for association of increases in temperature with antibiotic consumption

In the European surveillance study, McGough et al. [14] presented data indicating that higher antibiotic use is present in countries with higher mean temperatures. In Germany, Aghdassi et al. [18] suggested that an increase in HAIs may be expected when temperatures rise and these rising infection rates would then potentially lead to increased use of antibiotics.

3.5 Summary of climatic hazards that could aggravate AMR burden in Europe

In a recent study on the impact of climate hazards on pathogenic human diseases, Mora et al. [12] collected data on pathways in which climatic hazards, through different transmission routes, result in aggravation of specific diseases. They identified 43 articles worldwide with respect to climate change and information on pathogens causing the highest AMR burden in Europe according to Cassini et al. [4]. The results of these studies can be illustrated in a Sankey diagram of potential pathways through which climatic hazards could aggravate these pathogens (Figure 2). The most common pathogens found with an association to climatic hazards included *E. coli* (with 25 publications), followed by *S. aureus* (nine publications, four publications specifically for MRSA), *P. aeruginosa* (five publications) and *K. pneumoniae* (four publications). For these pathogens, the associated climatic hazards were floods, storms, warming, precipitation, and droughts. The main routes of transmission were waterborne transmission as well as unspecified transmission.

4. Discussion

4.1 Climate change and AMR

Climate change, through increases in temperature and changes in humidity and precipitation, will likely lead to bacterial pathogen spread, increased use of antibiotics and increased AMR in Europe. However, due to the complexity of interactions and the significance of various factors, we were not able not elucidate the full dimension of these associations. European data are scarce, and we were only able to identify six studies that met our inclusion criteria. However, all six of these studies pointed towards an overall further acceleration of increasing AMR burden due to climate change.

There is some evidence specifically demonstrating the increase in AMR with increasing temperatures in Europe [13, 14]. Studies outside of Europe verify these results. A study from the United States by MacFadden et al. [10] found that an increase in local minimum temperature is associated with increasing antibiotic resistance rates. However, this does not apply to all pathogens, and further factors like hygiene measures need to be considered. EARS-Net data reveal decreasing MRSA incidence in Europe, for example [14]. Hansen et al. [21] found that countries with decreasing MRSA proportions showed especially strict implementation of various prevention measures. The studies considered in our review also observed an increase in HAIs associated with an increase in temperature. SSIs and ha-BSIs in Germany, mostly due to gram-negative bacteria, occurred more frequently in warmer temperatures (≥20°C). In line with these findings, a study from Japan by Kobayashi et al. [22] concluded that SSIs are associated with summer months

(July–September, Hazard Ratio: 1.53, 95% CI: 1.06–3.83). Moreover, SSI rates were higher in summer months compared to non-summer months (3.9% vs. 1.9%, $p<0.05$). However, another study from Japan found contrasting results: Sagara et al. [23] ascertained that infections of the eye were most frequent in the winter months and less frequent in the summer and autumn months. Yet, when they stratified results by pathogens, they found that infections caused by *S. aureus* were more frequent in summer and autumn compared to colder seasons. *Streptococcus* spp. infections were more common in spring and summer months. Another surveillance paper concentrating on AMR genes and their distribution on a global level, taking climatic factors into account, found an uneven distribution of AMR genes in bacteria across several cities worldwide, suggesting an association with higher temperatures in different regions [24]. More evidence is needed to fully understand the associations between climatic factors and AMR, but existing evidence is sufficient to foresee that without appropriate interventions, climate change and the burden of AMR will continue to increase.

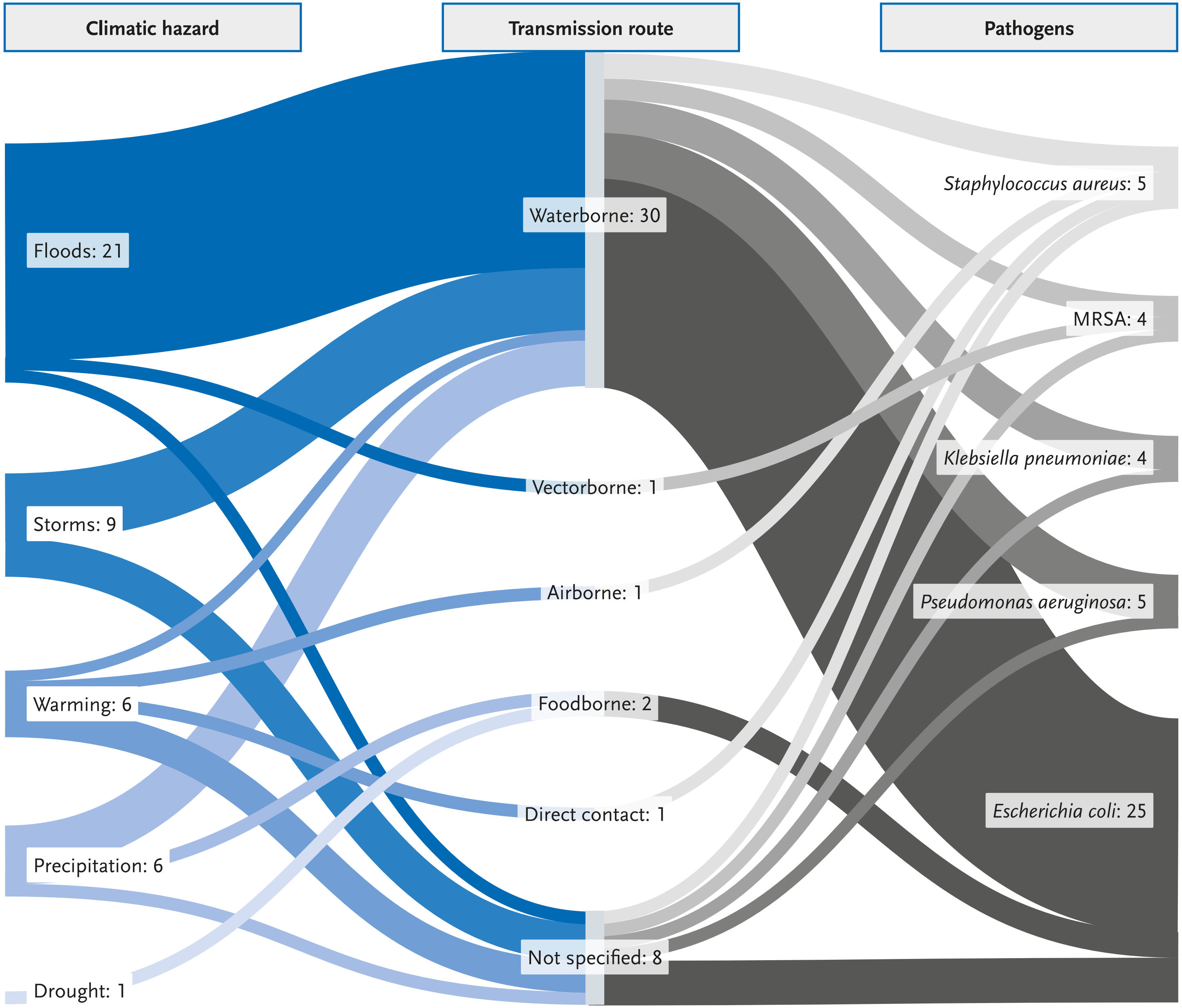
Climate hazards can bring humans and disease-causing organisms closer together, leading to a rise in pathogen transmission and infections, as demonstrated in our illustrated model with data from Mora et al. [12] (Figure 2). An increase in extreme weather events and natural disasters may cause disruptions and conditions that lead to an increase of AMR and pathogen spread as well as an increase in related antibiotic use. Such events can also lead to population displacement and increased burden on health systems which can further aggravate the spread of AMR and HAIs [25]. We focused on the AMR bacterial pathogens currently causing the highest burden in Europe. However, beyond the burden of infections with antibiotic-resistant bacteria, resistance to antimicrobial drugs such as resistance to antimalarial medications or antiretroviral therapy may also be increased by climate change [26]. Furthermore, the climate crisis could allow for the emergence and spread of new and re-emerging threats. For example, it has been suggested that *Candida auris*, a fungal pathogen that is often multi-drug-resistant and exists in the environment, may become increasingly pathogenic due to climate change [27]. In addition, recent studies indicate a potential threat for public health caused by the release of bacteria as well as viruses from thawing permafrost due to defrosting as a result of climate change [28, 29].

Overuse of antimicrobial drugs across human, animal and environmental sectors exacerbates AMR.

4.2 One Health and AMR

Human pathogen colonisation and infection can result from exposure to pathogens across a range of community and healthcare system domains and may be influenced by socioeconomic and environmental determinants of health. With our focus on human health, we did not comprehensively assess the changes in AMR from a One Health perspective, although we partly highlight this aspect by taking the review by Forrester et al. [15] into account, which includes the One Health perspective. AMR is rising in humans, animals, plants and the environment [30], and these increases may all be influenced by global and local temperatures rising due to climate change. One Health drivers (i.e. human and animal populations as well as the environment) and interactions related to infectious diseases and AMR can be illustrated as seen in Figure 3. Such interactions can often only be retrospectively analysed and their significance is likely to

Figure 2
Summary of climatic hazards that may modify the spread and health burden of resistant pathogens.
Full interactive display of all pathways and the underlying data are available [20].
Source: Webtool by Mora et al. [12, 20]



MRSA = meticillin-resistant *Staphylococcus aureus*

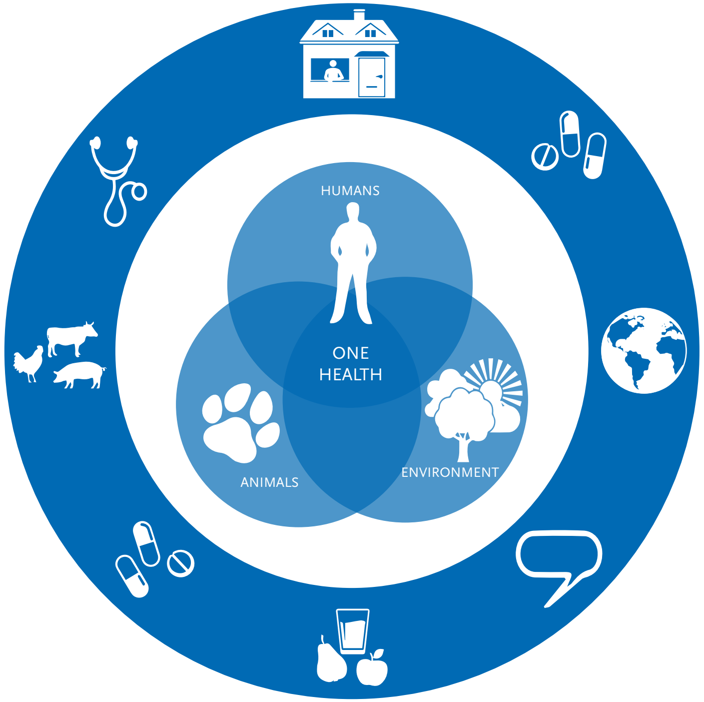


Figure 3
One Health drivers and interactions related to infectious diseases and antimicrobial resistance. Humans, animals and the environment (centre) influence AMR through drug use in humans and animals, nutrition, livestock, communication, healthcare personnel and facilities (outer circle).
Illustration: Robert Koch Institute

be underestimated in studies. As current evidence is pointing towards the aggravation of the existing AMR pandemic due to climate change, better data and public health action in human, animal, and environmental health domains are needed.

4.3 Limitations of this review

Possible limitations of our analysis are related to the limited number of studies included in this review. Among the excluded 35 non-European studies, there may be additional relevant evidence to better understand the association of climate change and AMR.

For included studies, the predominant study type was observational, where surveillance data of pathogens or infection were combined with climate data in form of an ecological study design. Here, measuring errors may occur in exposure and outcome leading to risk of bias and imprecision of the reported estimates. Even though various confounders were addressed within the single studies, there may be additional factors with influence on the association of climate and AMR or HAIs. By focusing on EU/EEA countries in this review, confounding due to societal and economic factors may have been reduced. Nonetheless, their potential relevance for AMR has been demonstrated before and should be kept in mind.

The two publications by Aghdassi et al. [16, 18] included in our review, should be considered together, as they use the same dataset. Those studies, as well as the one by Schwab et al. [17] were included, as we assume that an increase of HAIs will consecutively lead to an increasing AMR burden and thus may be considered as indirect evidence.

5. Conclusion and recommendations

The links between AMR and climate change require significantly more attention. Further detailed studies with local data on weather conditions, resistance situation, infectious diseases, but also antibiotic use, social determinants and other infectious and social factors are needed to better understand the pathways and subsequent impacts of these associations. Financial and scientific resources need to be made available to realise these studies. The example of decreasing MRSA incidence in many EU countries due to targeted public health action, in particular infection prevention and control measures in hospitals, is a reassuring sign that the AMR pandemic can be controlled. But climate change will likely make the control of AMR more challenging. On the other hand, there may be synergistic effects (or co-benefits) when leveraging action against both AMR and climate change, for example through reduction of industrial livestock farming or meat production and consumption. Although this summary focused on evidence in Europe, AMR is a pandemic threat. The Global South often suffers from a higher burden of AMR. Thus, prevention and control of AMR will have limited success with single country interventions and needs a global focus.

Despite the complexity of climate change processes and AMR, it will be important to closely monitor the changes in AMR over time in order to inform the prioritisation of public health measures. Intensified One Health surveillance approaches will be needed. Global surveillance systems such as the European EARS-Net and the worldwide Global Antimicrobial Resistance and Use Surveillance System (GLASS) are particularly important for country comparisons and could enable ecological studies analysing associations with regional climate change. Globally, we will have to further improve the availability and standardisation of antimicrobial susceptibility testing (AST), particularly in the Global South, to allow for more representative AMR surveillance data. In addition, AMR burden of disease studies will have to be developed and routinely updated to inform timely public health decision-making.

In addition to improved One Health AMR surveillance, universal health coverage and effective infection prevention and control measures including reliable access to water, sanitation and hygiene and One Health antimicrobial stewardship are needed to control the AMR pandemic worldwide. Investment in research and development on new antimicrobial drugs is needed as well as on the development of relevant vaccines.

More financing, political advocacy and coordinated global action are needed to better respond to the threats of antimicrobial resistance and the climate crisis.

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Conflicts of Interest

The authors declared no conflicts of interest.

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References

1. EclinicalMedicine (2021) Antimicrobial resistance: A top ten global public health threat. EClinicalMedicine 41:101221
2. World Health Organization (2019) Ten threats to global health in 2019. https://www.who.int/news-room/spotlight/ten-threats-to-global-health-in-2019 (As at 18.01.2023)
3. Murray CJL, Ikuta KS, Sharara F et al. (2022) Global burden of bacterial antimicrobial resistance in 2019: A systematic analysis. Lancet 399(10325):629–655
4. Cassini A, Högberg LD, Plachouras D et al. (2019) Attributable deaths and disability-adjusted life-years caused by infections with antibiotic-resistant bacteria in the EU and the European Economic Area in 2015: A population-level modelling analysis. Lancet Infect Dis 19(1):56–66
5. European Antimicrobial Resistance Collaborators (2022) The burden of bacterial antimicrobial resistance in the WHO European region in 2019: A cross-country systematic analysis. Lancet Public Health 7(11):e897–e913
6. European Centre for Disease Prevention and Control (ECDC), Organisation for Economic Co-operation and Development (OECD) (2019) Antimicrobial resistance – Tackling the burden in the European Union. ECDC, OECD. https://www.oecd.org/health/health-systems/AMR-Tackling-the-Burden-in-the-EU-OECD-ECDC-Briefing-Note-2019.pdf (As at 18.01.2023)
7. National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (2022) Monthly global climate report for annual 2021. NOAA. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202113 (As at 18.01.2023)
8. Ratkowsky DA, Olley J, McMeekin TA et al. (1982) Relationship between temperature and growth rate of bacterial cultures. J Bacteriol 149(1):1–5
9. Hashimoto M, Hasegawa H, Maeda S (2019) High temperatures promote cell-to-cell plasmid transformation in *Escherichia coli*. Biochem Biophys Res Commun 515(1):196–200
10. MacFadden D, McGough S, Fisman D et al. (2018) Antibiotic resistance increases with local temperature. Nat Clim Chang 8:510–514
11. Page MJ, McKenzie JE, Bossuyt PM et al. (2021) The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ 372:n71
12. Mora C, McKenzie T, Gaw IM et al. (2022) Over half of known human pathogenic diseases can be aggravated by climate change. Nat Clim Chang 12(9):869–875
13. Kaba HEJ, Kuhlmann E, Scheithauer S (2020) Thinking outside the box: Association of antimicrobial resistance with climate warming in Europe – A 30 country observational study. Int J Hyg Environ Health 223(1):151–158
14. McGough SF, MacFadden DR, Hattab MW et al. (2020) Rates of increase of antibiotic resistance and ambient temperature in Europe: A cross-national analysis of 28 countries between 2000 and 2016. Euro Surveill 25(45):1900414
15. Forrester JD, Cao S, Schaps D et al. (2022) Influence of socio-economic and environmental determinants of health on human infection and colonization with antibiotic-resistant and antibiotic-associated pathogens: A scoping review. Surg Infect (Larchmt) 23(3):209–225
16. Aghdassi SJS, Schwab F, Hoffmann P et al. (2019) The association of climatic factors with rates of surgical site infections: 17 years' data from hospital infection surveillance. Dtsch Arztebl Int 116(31–32):529–536
17. Schwab F, Gastmeier P, Hoffmann P et al. (2020) Summer, sun and sepsis – The influence of outside temperature on nosocomial bloodstream infections: A cohort study and review of the literature. PloS One 15(6):e0234656

18. Aghdassi SJS, Gastmeier P, Hoffmann P et al. (2021) Increase in surgical site infections caused by gram-negative bacteria in warmer temperatures: Results from a retrospective observational study. Infect Control Hosp Epidemiol 42(4):417–424
19. Kramer TS, Schröder C, Behnke M et al. (2019) Decrease of methicillin resistance in *Staphylococcus aureus* in nosocomial infections in Germany – A prospective analysis over 10 years. J Infect 78(3):215–219
20. Camilo Mora (2022) Traceable evidence of the impacts of climate change on pathogenic human diseases https://camilo-mora.github.io/Diseases/ (As at 18.01.2023)
21. Hansen S, Schwab F, Asensio A et al. (2010) Methicillin-resistant *Staphylococcus aureus* (MRSA) in Europe: Which infection control measures are taken? Infection 38(3):159–164
22. Kobayashi K, Ando K, Kato F et al. (2021) Seasonal variation in incidence and causal organism of surgical site infection after PLIF/TLIF surgery: A multicenter study. J Orthop Sci 26(4):555–559
23. Sagara H, Yamamoto T, Sekiryu T et al. (2016) Seasonal variation in the incidence of late-onset bleb-related infection after filtering surgery in Japan: The Japan Glaucoma Society survey of bleb-related infection report 3. J Glaucoma 25(1):8–13
24. Danko D, Bezdan D, Afshin EE et al. (2021) A global metagenomic map of urban microbiomes and antimicrobial resistance. Cell 184(13):3376–3393.e17
25. Global Leaders Group on Antimicrobial Resistance (2021) Antimicrobial resistance and the climate crisis. https://www.amrleaders.org/resources/m/item/antimicrobial-resistance-and-the-climate-crisis (As at 18.01.2023)
26. Fernando SD (2020) Climate change and malaria – A complex relationship. United Nations Chronicle. https://www.un.org/en/chronicle/article/climate-change-and-malaria-complex-relationship (As at 06.02.2023)
27. Casadevall A, Kontoyiannis DP, Robert V (2021) Environmental *Candida auris* and the global warming emergence hypothesis. mBio 12(2):e00360–00321
28. Kim H, Kim M, Kim S et al. (2022) Characterization of antimicrobial resistance genes and virulence factor genes in an Arctic permafrost region revealed by metagenomics. Environ Pollut 294:118634
29. Alempic JM, Lartigue A, Goncharov AE et al. (2023) An update on eukaryotic viruses revived from ancient permafrost. Viruses 15(2):564
30. OECD, ECDC, European Food Safety Authority (EFSA), European Medicines Agency (EMA) (2022) Antimicrobial resistance in the EU/EEA: A One Health response. OECD, ECDC, EFSA, EMA. https://www.ecdc.europa.eu/sites/default/files/documents/antimicrobial-resistance-policy-brief-2022.pdf (As at 18.01.2023)

Annex Table 1
Applied search string

Database	Search strategy
PubMed	("climate change"[MeSH Terms] OR "global warming"[MeSH terms] OR "climatic processes"[MeSH terms] OR ("climate*"[Title/Abstract] AND "change*"[Title/Abstract]) OR "climate*"[Title/Abstract] OR "temperature*"[Title/Abstract]) AND ("Anti-Bacterial Agents"[MeSH Terms] OR "Drug Resistance, Bacterial*" [MeSH Terms] OR "health care associated infection" [Title/Abstract] OR "nosocomial"[Title/Abstract] OR "AMR" [Title/Abstract] OR "antimicrobial resistance*"[Title/Abstract] OR "antimicrobial resistan*"[Title/Abstract] OR "antibiotic*"[Title/Abstract]) AND ((y_10[Filter]) AND (humans[Filter]))

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