Future scenarios of risk of *Vibrio* infections in a warming planet: a global mapping study

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Summary

Background Infections caused by non-cholera *Vibrio* species have undergone a global expansion over the past few decades reaching new areas of the world that were previously considered adverse for these organisms. The geographical extent of the expansion has not been uniform, and some areas have shown a rapid increase in infections.

Methods We applied a new generation of models combining climate, population, and socioeconomic projections to map future scenarios of distribution and season suitability for pathogenic *Vibrio*. We used the Coupled Model Intercomparison Project 6 framework. Three datasets were used: Geophysical Fluid Dynamics Laboratory's CM4.0 sea surface temperature and sea surface salinity; the coastline length dataset from the World Resources Institute; and Inter-Sectoral Impact Model Intercomparison Project 2b annual global population data. Future projections were used up to the year 2100 and historical simulations from 1850 to 2014. We also project human population at risk under different shared socioeconomic pathways worldwide.

Findings Projections showed that coastal areas suitable for *Vibrio* could cover 38 000 km of new coastal areas by 2100 under the most unfavourable scenario with an expansion rate of season suitability in these regions of around 1 month every 30 years. Population at risk in suitable regions almost doubled from 1980 to 2020 (from 610 million to 1100 million under the scenario of medium challenges to mitigation and adaptation, shared socioeconomic pathway 2-4.5), although the increment will be more moderate in the future and stabilises after 2050 at 1300 million. Finally, we provide the first global estimate for *Vibrio* infections, with values around half a million of cases worldwide in 2020.

Interpretation Our projections anticipated an expansion of both the temporal and spatial disease burden for *Vibrio* infections, in particular at high latitudes of the northern hemisphere. However, the largest extent occurred from 1980 to 2020 and a more moderate increase is expected for the future. The most positive outcome is that the projections showed that *Vibrio* morbidity will remain relatively stable over the coming decades.

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Introduction

Climate change is impacting the planet in an unprecedented way, causing rapid changes across all ecological scales. Particularly relevant are the implications on those aspects directly and indirectly associated with health. Changes in weather patterns as result of climate change are also affecting some basic social and environmental determinants of health, such as clean air, safe drinking water, sufficient food, and secure shelter.[1] In addition, climate change is altering infection patterns for some diseases that are particularly sensitive to ecological changes. This situation is especially pertinent for vector-borne diseases (eg, malaria and dengue) because of the extension of the transmission season at local scale and the expansion of the distribution range for disease vectors.[2,3] A second important group of human pathogens that are currently undergoing a rapid growth is *Vibrio*. The genus *Vibrio* comprises more than 100 species that are natural inhabitants of aquatic and marine environments with warm waters and low to moderate salinity.[4] To date, 12 *Vibrio* species have been reported as causes of infections in humans.[4] In addition to *Vibrio cholerae*, the causative agent of cholera epidemics (serogroups O1 and O139), other *Vibrio* species can cause infections normally acquired as wound infections from exposure to seawater or gastrointestinal illness associated with consumption of raw or undercooked seafood.[4,5] These non-cholera *Vibrio* spp (primarily *Vibrio parahaemolyticus*, *Vibrio alginolyticus*, *Vibrio vulnificus*, and non-toxigenic [non-O1 or non-O139 serogroups] *V cholerae*) cause vibriosis, which can lead to several clinical manifestations. The most common symptoms are mild and self-limiting gastroenteritis, but skin infections can also be caused when an open wound is exposed to seawater.[6] The incidence of vibriosis has been rising over the past few decades and cases are being reported in remote regions with no precedents for this disease, and where environmental conditions had been considered adverse for pathogenic *Vibrio*. The rise of sea water temperature, as a result of climate change, has

Research in context

Evidence before this study

Several previous studies have shown a continuing rise of non-cholera *Vibrio* infections (vibriosis) worldwide over the past few decades. Cases have emerged in new regions following a well defined poleward expansion. Previous models tried to delineate the extent of the geographical expansion based on the ecological preferences of *Vibrio* for warm waters of moderate salinity, and provided projections according to different climatic scenarios. However, socioeconomic and demographic aspects, which have been identified as key elements in disease transmission, have not yet been reported. Here, we applied a new generation of models, within the Coupled Model Intercomparison Project 6 (known as CMIP6) framework, that provide a wider range of possibilities and more robust projections, introducing an increasing resolution and comprehensiveness to understand the impact of climate change. These models were integrated into the new shared socioeconomic pathways, which consider socioeconomic drivers—economic growth, demography, education and technological development—that can impact the future emissions of greenhouse gases and represent different adaptation and mitigation challenges.

Added value of this study

We made use of climate, population, and socioeconomic projections to generate more accurate estimates of past, present, and future changes in *Vibrio* suitability and population at risk of vibriosis worldwide. The study identified changes in *Vibrio* distribution since the preindustrial era (1850), applying, for the first time, this period as baseline to gain a more precise understanding about the effect of climate change in modulating future scenarios. Additionally, this study is the first to provide a global estimate of the population at risk of vibriosis for different periods.

Implications of all the available evidence

This work and projections provide key components to visualise the global changes and threat associated with *Vibrio* illness. Results of this study can be applied to generate a new generation of early warning systems to identify and forecast areas and periods of risk. The information will help public health policy makers to create more robust intervention plans and anticipate responses to future scenarios of *Vibrio* risk.

been identified as one of the major drivers of disease emergence, in particular at locations in high latitudes.[7,8]

The ecology of *Vibrio* has been intrinsically associated with two main environmental factors: seawater temperature and salinity. These two elements have been identified as the main components governing the distribution and abundance of *Vibrio* in coastal waters.[9,10] Basically, salinity defines the areas suitable for these organisms, while temperature modulates the abundance in those areas suitable for presence. The typical response of *Vibrio* abundance to shifts in seawater temperature is characterised by rapid growth after a specific threshold value; that for pathogenic *Vibrio* has been established at around 18°C.[11] Although the cause and effect relationships of climate change are complex and can lead to multidirectional effects, the rise of seawater temperature and altered salinity of the seas are the two most visible effects of climate change in coastal areas. Consequently, the distribution of *Vibrio* populations and the resultant disease dynamics are going to be greatly affected by the presence of warmer and less saline coastal waters. Around 71% of the world's coastlines are substantially warming, with rates of change varying between regions both spatially and seasonally.[12] In enclosed bodies of water and estuaries, the sea surface temperature has increased more rapidly as a result of climate change than it has in oceans.[13] In parallel, changes in precipitation, river runoff, and ice melt can lead to a temporal reduction of salinity in many coastal areas under a warming trend, which might contribute to the generation of new areas with ideal environmental conditions for the growth of *Vibrio* species.[14–16] As a result of these changing conditions, the number of days suitable for *Vibrio* has increased since an early 1980s baseline, and global suitability for coastal *Vibrio* has increased by 9·9% over this period.[3]

For the **coastline length dataset** see http://ede.grid.unep.ch

This basic knowledge of *Vibrio* ecology has been applied to build models and develop monitoring systems based on remote-sensing data. These models were able to assess the risk of *Vibrio* infections in coastal regions and were used as early warning systems for disease prevention. In this particular context, the European Centre for Disease Prevention and Control (ECDC) developed a web-based tool (the ECDC Vibrio Map Viewer) using the operational *Vibrio* fields provided by NOAA CoastWatch to monitor environmentally suitable marine areas for *Vibrio* growth in almost real time.[11] The tool is based on a real-time model that uses sea surface temperature and sea surface salinity of coastal waters that are updated daily and remotely sensed as inputs to map areas of high suitability for *Vibrio*.[11] Forecasts derived from this tool have been regularly distributed among public health decision makers by the ECDC over the disease season in the Baltic region and have become a central component of the active early warning system for *Vibrio* infections.

Despite the substantial progress made with the ECDC Vibrio Map to provide a realistic proxy for the risk of *Vibrio* infections in almost real time, the tool worked only on the basis of two elements, sea surface temperature and salinity; however, other critical components with consequences for disease outcomes were needed. In particular, sociodemographic or behavioural aspects were not considered in this approach. The availability of a new generation of climate models, such as the Coupled Model Intercomparison Project (CMIP), provides a new opportunity to introduce increasing resolution and comprehensiveness (coupled and earth system models) into new warning systems. Previous analytical approaches were constructed under the framework of the Representative Concentration Pathways,[18] which describe different climate futures, but do not cover crucial socioeconomic developments, which are important factors to delineate the adaptation and mitigation in response to climate effects.[19] The new framework of the shared socioeconomic pathways (SSPs)[19] considered also socioeconomic drivers (eg, economic growth, demography, education, and technological development), which can also have a strong influence on the future emissions of greenhouse gases.[20] We have applied this new generation of climate, population, and socioeconomic projections to develop a new generation of *Vibrio* risk models to provide more accurate estimates of future changes in *Vibrio* suitability and population at risk.

Methods

In our study, we have applied a subset of the latest generation of CMIP data (CMIP6)[17] to map and analyse the past, present, and future risk of *Vibrio* infections worldwide. We projected future scenarios of risks based on the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) framework[21] under two climate change scenarios: SSP2-4.5 (a middle-of-the-road scenario, with medium challenges to mitigation and adaptation), and SSP5-8.5 (a taking-the-highway scenario, with low challenges to mitigation and high challenges to adaptation) up to the year 2100, including historical simulations from the year 1850.

Within this scope, three datasets were used. (1) Geophysical Fluid Dynamics Laboratory's CM4.0[22] sea surface temperature and sea surface salinity from CMIP6 historical data (1850–2014), and future projections (2015–2100) by use of SSP2-4.5 and SSP5-8.5 experiments. Both variables are provided at monthly time steps and 25 km resolution, offering an improved coastal coverage compared with similar products at 0·5° resolution. (2) The coastline length dataset from the World Resources Institute was used to estimate the trends (km/year and per country) in the length of coastline affected by *Vibrio* favourable conditions. (3) ISIMIP2b annual global population data at 0·5° resolution for the period 2006–2100 (SSP2-4.5 and SSP5-8.5) and 1850–2015 (historical) were used to estimate the population potentially affected by *Vibrio* infections.[23] Our method

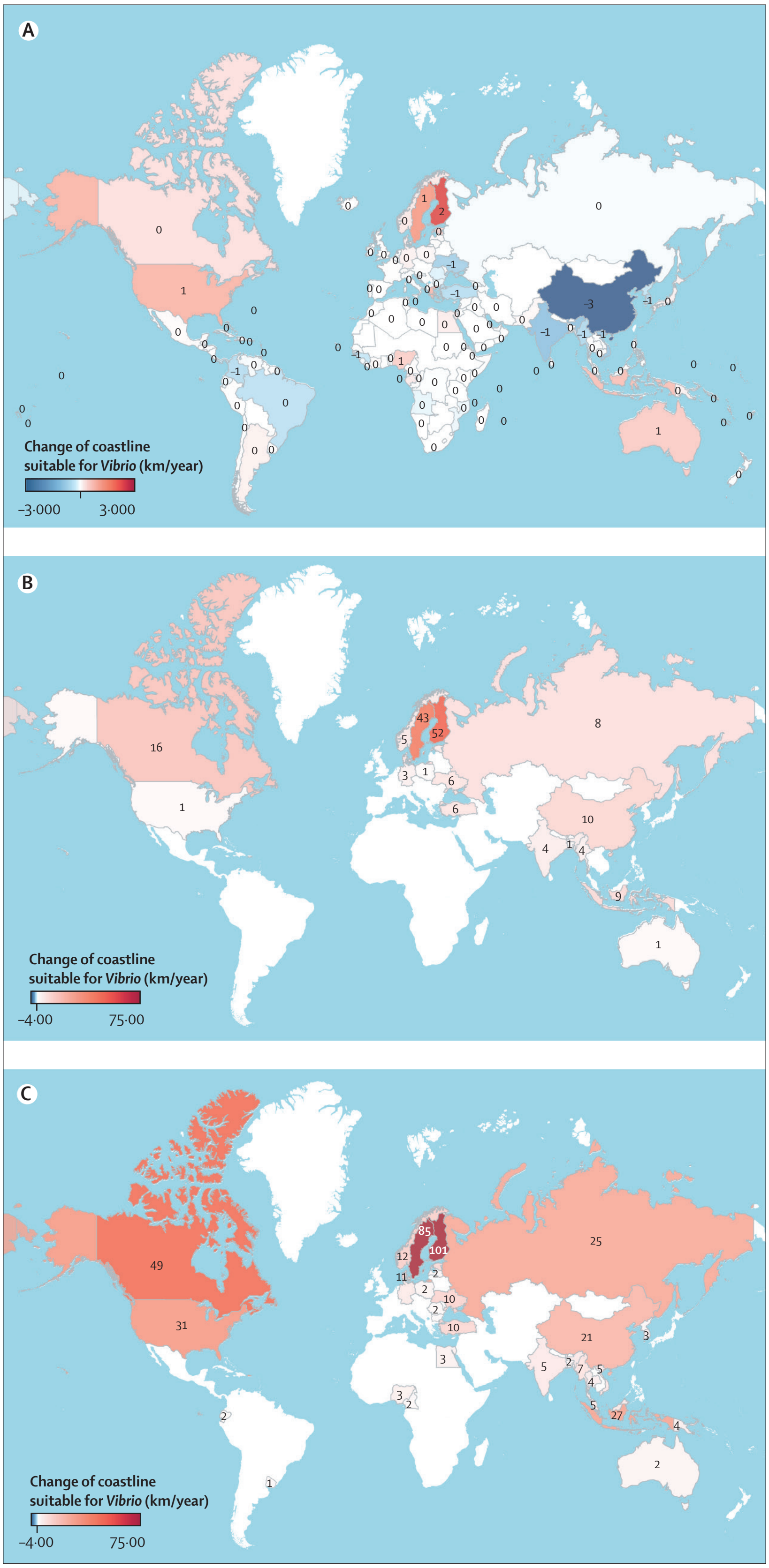


Figure 1: **Maps showing the increment in km/year of coastline with conditions suitable for *Vibrio* in each country**
Historical period of 1850–2014 (A), and under SSP2-4.5 (B) and SSP5-8.5 (C) scenarios for the period 2015–2100. SSP=shared socioeconomic pathway.

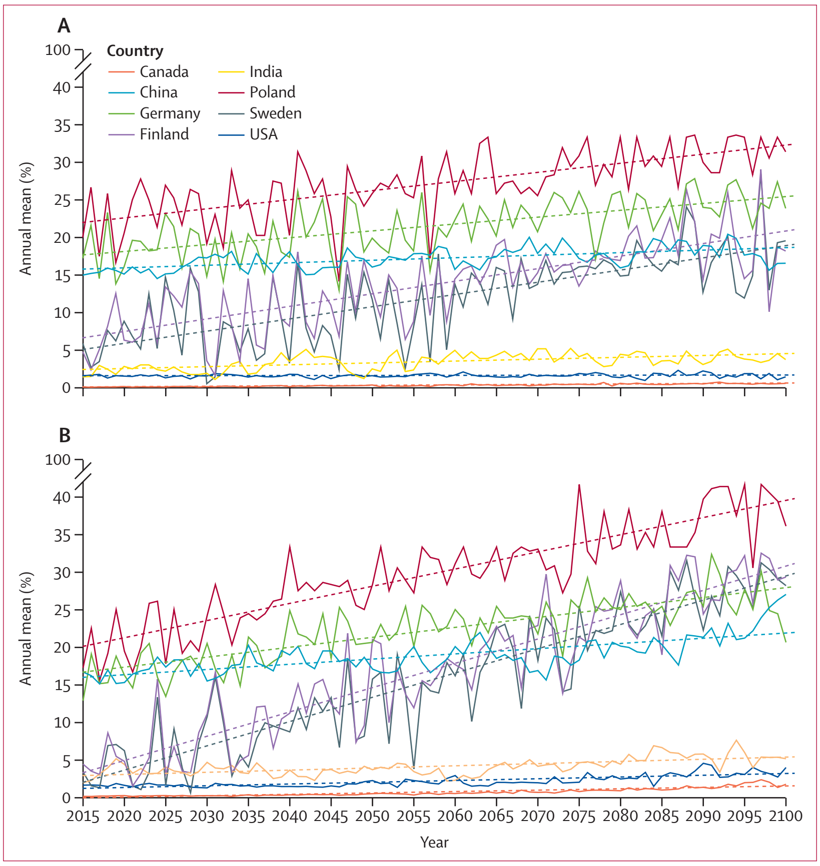


Figure 2: **Time series showing the variation of shoreline with suitable conditions for *Vibrio* for a selection of countries**
SSP2-4.5 (A) and SSP5-8.5 (B) scenarios over the period 2015–2100. SSP=shared socioeconomic pathway.

considered a maximum distance of 100 km between the pixel showing *Vibrio* suitability and the centre of the population cell. Our simulations for each scenario used the corresponding socioeconomic population dataset.

Vibrio ecological suitability

The *Vibrio* suitability regions were determined on the basis of a threshold-based approach for sea surface temperature and salinity estimates. Those areas showing temperatures above 18°C and salinities below 28 psu were flagged as suitable for *Vibrio*. These thresholds were used considering previous studies[8,11] and match the values currently being used for the *Vibrio* global suitability fields. The threshold value for salinity is well below the usual ranges in most of the open ocean, and takes into account the potential local decreases due to freshwater fluxes into the ocean (eg, precipitation, runoff, etc), making the estimate conservative. For sea surface temperature and salinity, only those cells closer than 30 km to coastline were analysed. This band represents the areas in which human exposure to *Vibrio* via direct contact with water is at a maximum, and also the region where most aquaculture-related activities, another core source of vibriosis, take place. The corresponding time series allowed us to determine the percentage of coastline showing suitable conditions for *Vibrio*. This processing was undertaken by country and WHO region, for the purpose of providing regional-scale projections using, in our case, the mean average annual percentage to estimate the linear trend for all the proposed scenarios. These results are combined with the coastline length dataset to evaluate the trend in km/year, with the same granularity as in our previously mentioned analysis. These results serve as a basis to evaluate the variation in the number of months per year where suitable conditions for *Vibrio* are present for each pixel. Normalising this value for the historical, SSP2-4.6, and SSP5-8.5 scenarios gives us a clear indication of the new hot spots for *Vibrio* worldwide.

Population at risk

An important component in disease transmission is the population at risk in a particular region. This aspect is even more relevant for *Vibrio* due to its restrictive distribution within marine waters close to the coast. Currently, 40% of the world's urban population lives in coastal areas and an important number of goods and services are obtained from coastal-marine ecosystems.[24] Within this context, shifts in population and demography in coastal areas undergoing a warming trend are going to play a major role in shaping the population exposed to *Vibrio*. The population potentially affected by exposure to *Vibrio* has been selected on the basis of the ad-hoc distance of 100 km between areas showing *Vibrio* suitability and the centre of the population cell for that time period. The associated time series provided a clear indication of the trend in the number of people living in the vicinity of areas suitable for *Vibrio* for the different scenarios. We did a similar analysis keeping the population constant, using as reference the population for the year 2014, to evaluate the effect of changes solely due to the variation in the geographical distribution of *Vibrio* suitable areas under the different scenarios.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

The analysis of the historical trend with data from 1850 to 2015 showed a negative mean value on a global basis for the extension of areas with suitable ecological conditions for pathogenic *Vibrio*, with an average reduction of 2·26 km per year over the whole period of 165 years. However, despite this negative (although mostly small) general trend, some specific regions showed a positive trend over the period. In particular, some countries in the Baltic region (ie, Finland and Sweden) showed the strongest growth signal, with the USA, Gulf of Guinea, Australia, and southeast Asia also showing positive trends (figure 1A).

This negative or slightly positive trend in the historical data diverged from results obtained from projections under the SSP2-4.5 and SSP5-8.5 scenarios (figure 1B, C), which showed a clear pattern of expansion for *Vibrio* suitability of 183 km of coast per year globally for SSP2-4.5 and 449 km of coast per year globally for SSP5-8.5. According to these results, a total of 15 555 km of new coastal regions for the SSP2-4.5 scenario and 38 165 km for the SSP5-8.5 scenario will have reached favourable conditions for *Vibrio* by 2100. For SSP2-4.5, the region showing the strongest positive trend is the Baltic Sea, with an increase of 52 km/year for Finland, resulting in 4420 km by 2100, and 43 km/year for Sweden, resulting in 3655 km by 2100, covering 14% more coastline for both of these countries (figure 1B). Other countries that showed an expansion of coastal areas suitable for *Vibrio* were Canada (16 km/year), China (10 km/year), and Russia (8 km/year).

A similar geographical distribution of regions with the strongest positive trends for *Vibrio* suitability was found under the SSP5-8.5 scenario, but in this case with a much more positive rate of expansion: Finland 101 km/year, Sweden 85 km/year, Canada 49 km/year, Russia 25 km/year, and China 21 km/year (figure 1C). Distinctively, a strong positive trend was also noted for the USA under the SSP5-8.5 scenario, with values around 31 km/year.

The time series analysis of variation of shoreline that showed suitable conditions for *Vibrio* under the SSP2-4.5 scenario (figure 2 shows some representative entries) showed that countries with the highest rate of expansion for *Vibrio* suitability were mostly located around the Baltic Sea, with Latvia showing an increment of 15%, followed by Finland and Sweden both with a 14% increase (figure 3). Other large countries—such as Canada, the USA, and China, with long and highly populated coastlines—showed a neutral or slightly positive net trend, although some areas displayed a strong increase in *Vibrio* suitability. A similar pattern was observed under the SSP5-8.5 scenario, but with values doubling the trends inferred under the SSP2-4.5 scenario. Finland and Sweden showed an increase of 27% of coastline with suitable conditions for *Vibrio*, followed by Estonia (26%) and Latvia (25%). Uruguay also showed a strong trend of expansion under this scenario (11%).

Future changes in the length of areas with suitable conditions for presence of pathogenic *Vibrio* was also evaluated globally using historical data and the SSP2-4.5 and SSP5-8.5 scenarios as a proxy for changes in disease season. Historical data showed a neutral or almost neutral

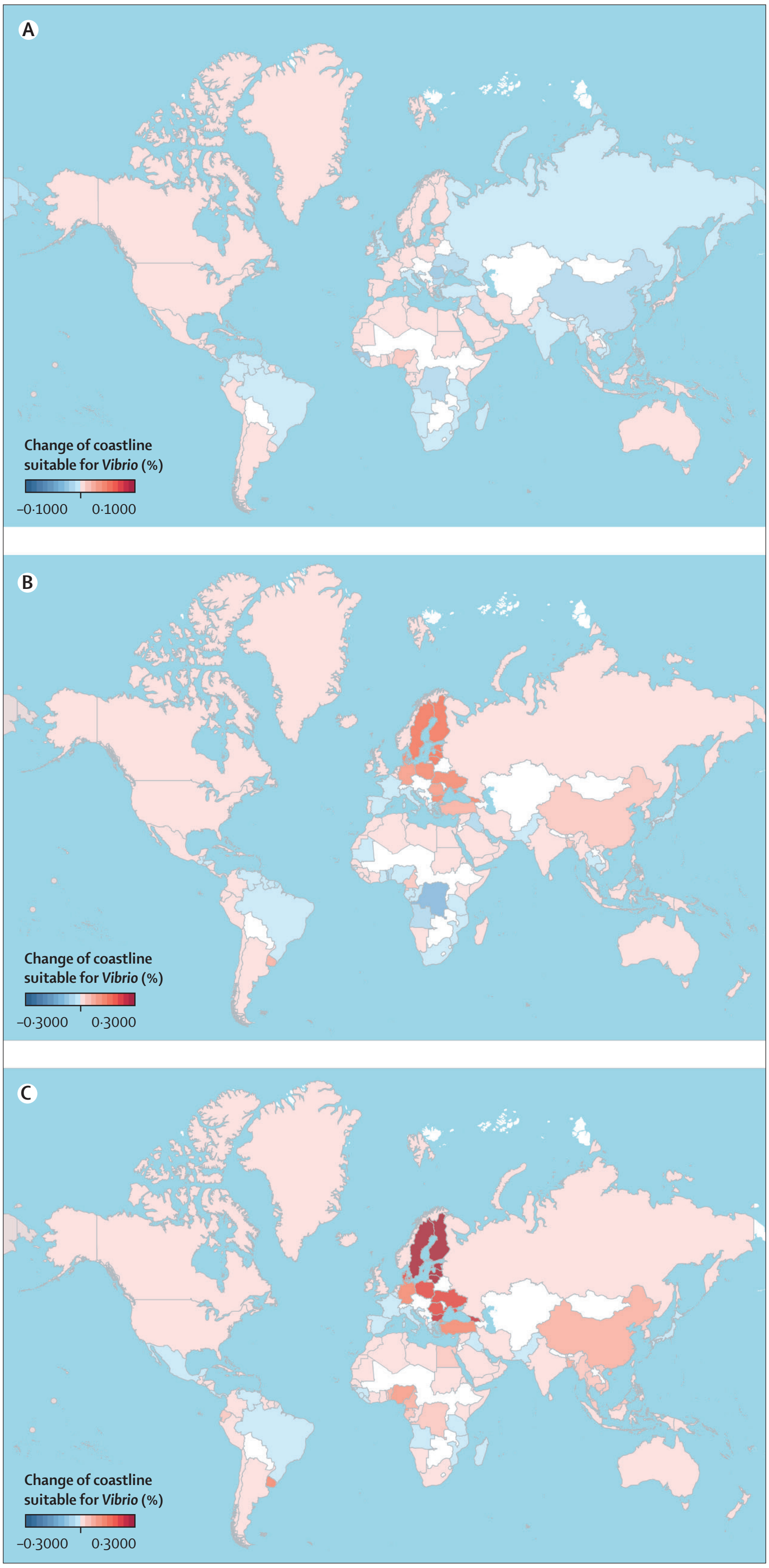
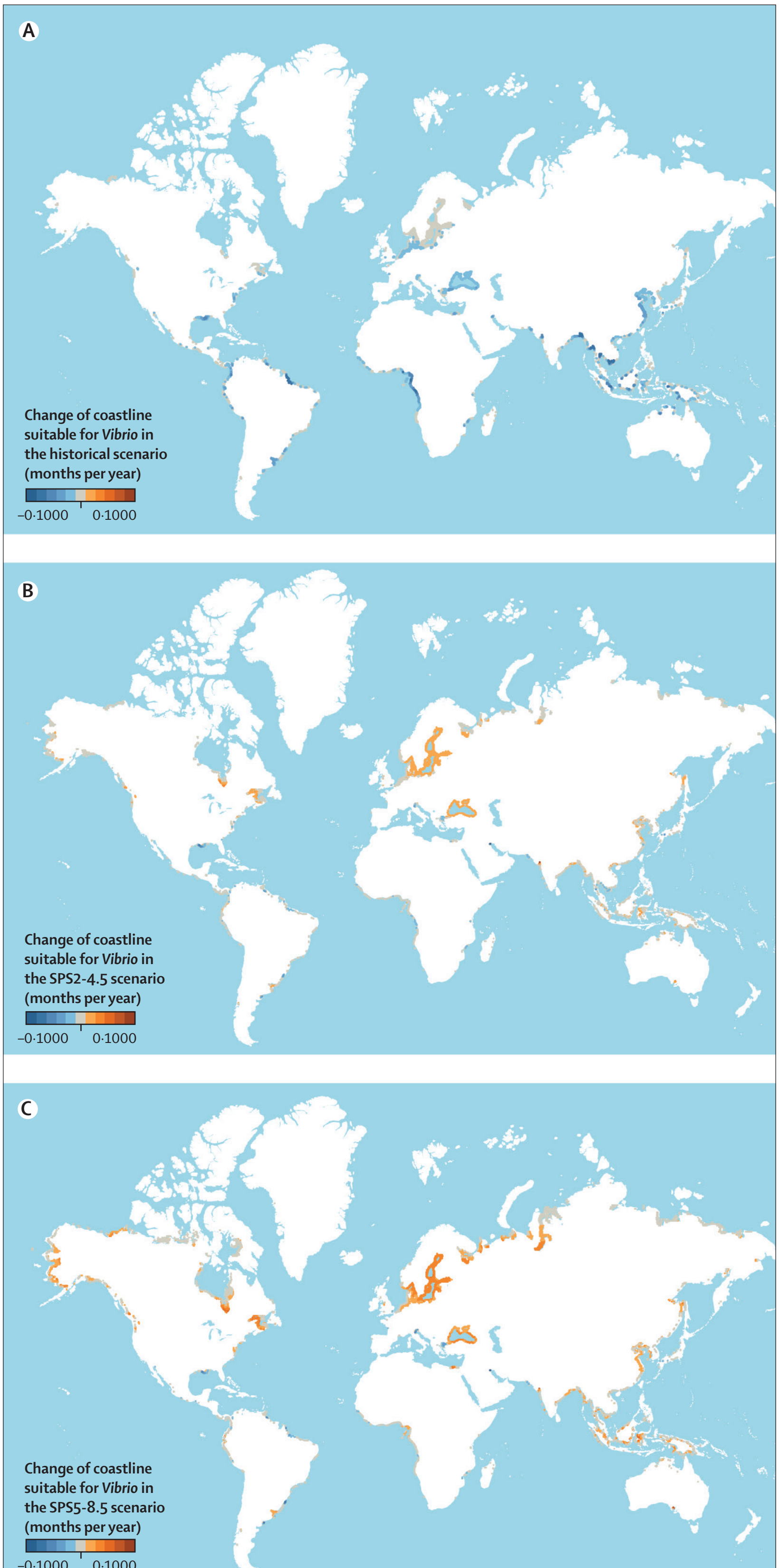


Figure 3:* Maps showing the percentage increment by year and country of coastline affected by conditions suitable for *Vibrio
The historical period of 1850–2014 (A) and under SSP2-4.5 (B) and SSP5-8.5 (C) scenarios for the period 2015–2100. SSP=shared socioeconomic pathway.



scenario with small negative trends in some regions of the world (figure 4). However, for the period 2015–2100 with the SSP2-4.5 and SSP5-8.5 scenarios, the trend was quite the opposite and showed a sharply positive growth in the number of months with suitable conditions for *Vibrio* under both SSP scenarios (figure 4). Specifically for SSP2-4.5, the regions with the strongest trend were identified around the Baltic Sea, Black Sea, and the northeast of North America with around 0·3 month increase every 10 years (more than 2 months by 2100). Other regions showing more moderate positive trends were southeast Asia, the Pacific northwest of North America, and Alaska, USA. A similar pattern of expansion in *Vibrio* season, but with increasing trends, was observed for the SSP5-8.5 scenario (figure 4), although in this case more areas of the northern hemisphere would be affected, particularly in high latitude regions of Russia and Canada.

To delineate which areas would be affected by the strongest expansion of *Vibrio* suitability compared with historical levels, the difference in the normalised number of months showing conditions for *Vibrio* between simulations for future scenarios and the historical baseline was calculated (figure 5). Results showed an expansion in the season suitability for *Vibrio* of up to 4 months, with respect to the historical baseline, in those hot spots of warming for both SSP2-4.5 and SSP5-8.5 scenarios. In addition to the Baltic region and the Atlantic northeast, Alaska and several areas in northern Russia showed a strong increase in the season suitability for *Vibrio* under both scenarios. Large regions of southeast Asia also showed a higher increase for SSP2-4.5 than for SSP5-8.5.

To investigate the potential impact of population dynamics on *Vibrio* infections, changes in the population living within 100 km from the coastline globally was assessed using the historical dataset and under SSP2-4.5 and SSP5-8.5 simulations (figure 6). Global populations living in coastal regions with suitable conditions for *Vibrio* grew over the past century and reached an estimated value of 610 million for 1980. The projection for 2020 duplicated the estimate for 1980, with a total 1107 million under SSP2-4.5 scenario, and 1133 million for SSP5-8.5. According to the simulations, this trend will continue to increase until 2050 and after this point the simulations showed a stabilisation in the projections or even a slight decline. Projected values in 2082 for SSP2-4.5 are estimated to reach 1388 million, and in 2069 for SSP5-8.5 are estimated at 1386 million people. Overall, similar trend patterns were observed for both SSP2-4.5 and SSP5-8.5 simulations.

***Figure 4:* Maps showing the increasing trend in the presence of conditions suitable for *Vibrio* by months per year**

The Coupled Model Intercomparison Project 6 historical simulation of 1850–2014 (A), and under future scenarios SSP2-4.5 (B) and SSP5-8.5 (C). SSP=shared socioeconomic pathway.

According to these projections, and applying a conservative assumption of infection rate per 100 000 population of 0·3 (as estimated by both the Cholera and Other Vibrio Illness Surveillance–US Centres for Disease Prevention and Control and FoodNet for the USA),[25] for 1980, 1830 cases were estimated, whereas for 2020, the numbers of projected cases were 3321 (SSP2-4.5 scenario) and 3401 (SSP5-8.5 scenario). In 2050, 3845 cases were estimated under the SSP2-4.5 scenario, and 3819 cases for the SSP5-8.5 scenario. However, a more realistic estimate of infection rate considering limitations of surveillance data and under-reporting in the USA, scaled up the number of infections by 143 times.[26] When we applied the under-reporting ratio to calculate a more probable incidence of disease, estimates changed substantially and values of infections reached values of 261 690 for 1980, 474 903 (SSP2-4.5) and 486 343 (SSP5-8.5) for 2020, and 549 835 (SSP2-4.5) and 545 974 (SSP5-8.5) for 2050.

Geographical areas with the largest population at risk reached values of 1 million inhabitants living within a 100 km radius of suitable areas for *Vibrio* (figure 6B, C). These regions were located in coastal areas of the north of Europe, southeast Asia, the Gulf of Guinea, the Atlantic northeast, the Pacific northwest, and some specific hot spots in the Gulf of Venice, the south coast of the Black Sea, and coastal areas of Egypt. New regions in high latitudes in the northern hemisphere that show populations at risk (figure 6C) are a clear indication of the poleward expansion of *Vibrio* infections.

Discussion

Vibrio infections are caused by a diverse group of pathogens with complex life cycles involving different stages as free-living bacteria as well as a component of the microbiome of different marine organisms. As a consequence, clinical manifestations and disease outcomes can also be diverse depending on the pathogen species, route of infection, and host susceptibility.[4] The deficit of reliable epidemiological data for vibriosis on a regional and global scale has become a major limitation to identified links between local environmental conditions and the onset of infections, as well as to building a basic knowledge on key elements of transmission, such as routes of exposure, changes in incidence, and geographical and epidemiological patterns associated with *Vibrio* infections. Only the retrospective scrutiny of environmental conditions during non-outbreak periods and during outbreaks in regions with robust epidemiological records—such as the Baltic Sea, or the USA—made possible the definition of the specific conditions that drive the onset of *Vibrio* infections.[8,11,27] Based on this knowledge, a first early warning system for *Vibrio* risk was developed.[11] This tool has provided for the first time a global estimate of areas and periods of *Vibrio* suitability and has become instrumental for public health awareness and risk communication.[11]

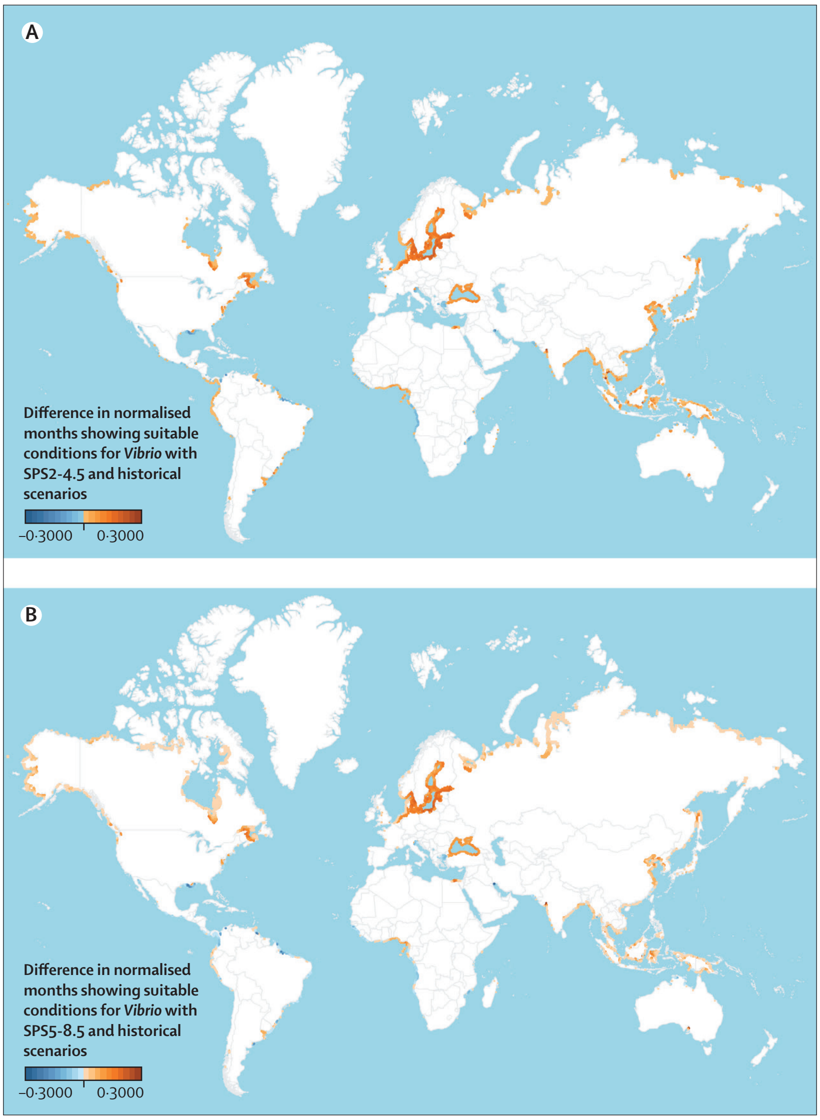


Figure 5: **Difference in the normalised number of months showing conditions for *Vibrio* between simulation for future scenarios (2015–2100) and the historical baseline (1850–2014)**
SSP2-4.5 (A) and SSP5-8.5 (B) scenarios. SSP=shared socioeconomic pathway.

Non-cholera *Vibrio* infections are expected to rise in the future. In addition to global warming, other key factors have been suggested as contributors to the rise of vibriosis: demographic changes and population growth in coastal areas, more frequent recreational use of waters, and new patterns of seafood consumption.[4,5,7] However, the net contribution of these socioeconomic and behavioural elements has remained uncertain. The availability of a new generation of climate models, with a wider prospect and more robust projections, has made it possible to introduce higher resolution and comprehensiveness into projections and gain a better understanding of climate changes.[28] CMIP6 includes assessments of model performance during the historical period (1850–2014) and quantifications of the causes of

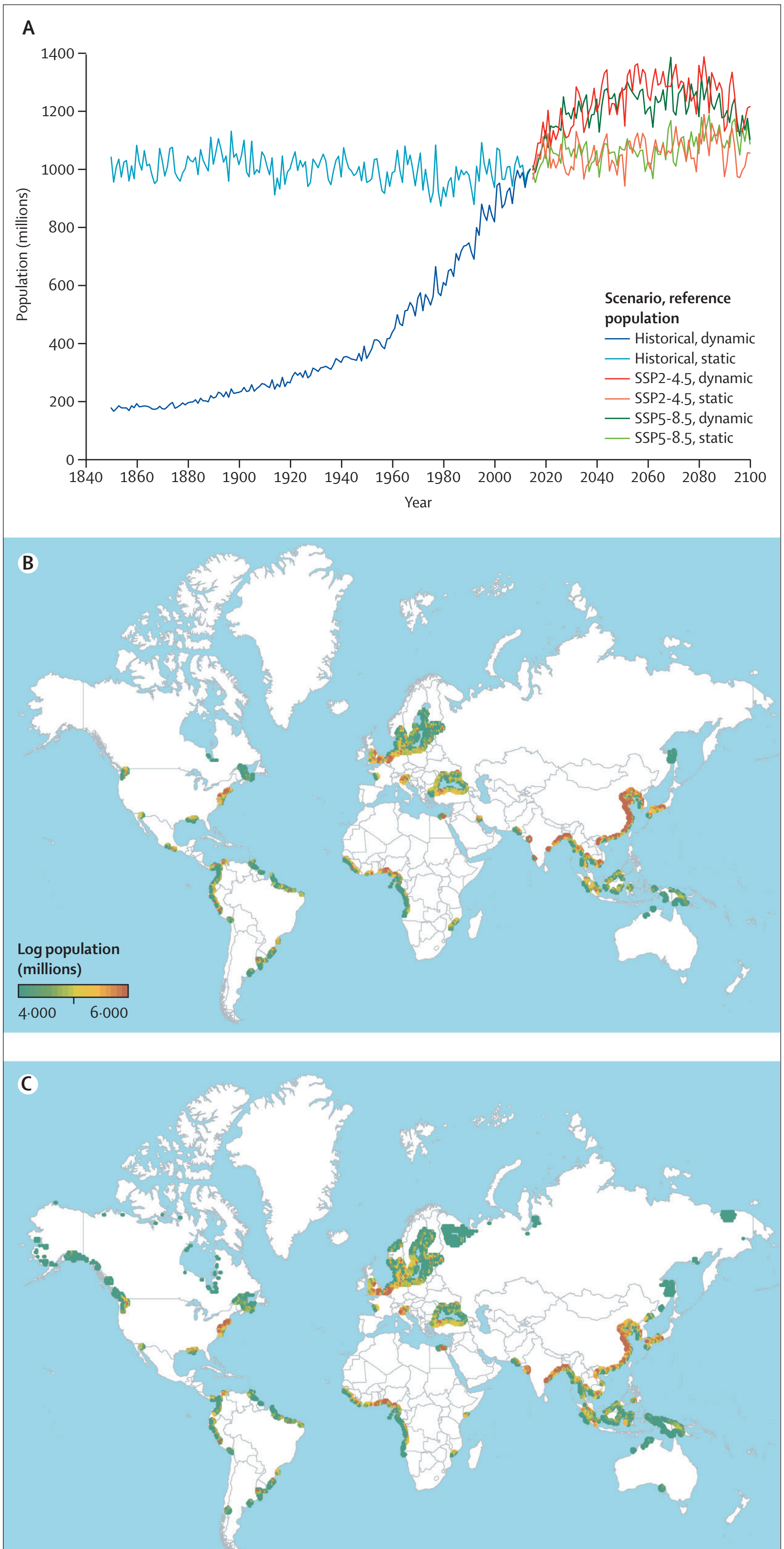


Figure 6: **Trends in population living in areas with suitable conditions for *Vibrio***

(A) Bold colours (ie, dark blue, dark orange, and dark green) indicate a combination of historical, SSP2-4.5, and SSP5-8.5 scenarios of populations living in areas with suitable *Vibrio* conditions within a 100 km radius (dynamic); population datasets correspond to each climate scenario. Light colours (ie, light blue, light orange, and light green) indicate a combination of populations living in areas with suitable *Vibrio* conditions within a 100 km radius for a constant 2014 population dataset (static). The *Vibrio* suitability fields were obtained from the Coupled Model Intercomparison Project 6 historical, SSP2-4.5, and SSP5-8.5 simulations. (B, C) Population exposed to coastal areas with suitable conditions for *Vibrio* within a 100 km grid for 2015 (B) and 2100 (C) under the SPS5-8.5 scenario. SSP=shared socioeconomic pathway.

the spread in future projections. Previous CMIP models did not provide a high-resolution account of coastal areas where *Vibrio* resides, and where the exposure to the pathogen occurs. CMIP6 offers higher resolution (eg, 25 km) and specifically covers areas near the coastline, which represents a substantial improvement with respect to previous models. Based on datasets from Geophysical Fluid Dynamics Laboratory's CM4.0, this study provides a first global estimate on the extent of progression since 1850 of *Vibrio* distribution and occurrence, and presents future projections under different climatic and socioeconomic scenarios. Projections predict a considerable expansion of both the temporal and spatial disease burden for these infections. Coastal areas suitable for *Vibrio* might include an additional 38 000 km of coast by 2100 under the most unfavourable scenario. In addition to the new coastal areas gained for *Vibrio*, the season suitability for these pathogens will expand, such that disease conditions will be reached in more places, but also for longer periods with an expansion rate of around 1 month every 30 years. The results corroborated previous findings[7,8] and new areas have been identified at high latitudes of the northern hemisphere where environmental conditions for *Vibrio* had been considered adverse until a few years ago. One of the benefits of CMIP6 is that it provides an ideal framework to further refine estimates by including data from other models and additional scenarios. Some crucial factors, such as the assessment of the effect of sea level change on the coastal zone in regions exposed to *Vibrio* risk and demographic and exposure factors, have not been considered in the present work. The integration of these new datasets will be the subject of future work.

SSPs offer the possibility of integrating climate and socioeconomic drivers (eg, economic growth, demography, education, and technological development) into the models and simulations. This particularity has enabled development, for the first time, of projections for human population at risk. Demographic changes had been proposed as key elements contributing to the increase in vibriosis, including the growth of populations living on the coast and larger susceptible or at risk population as a consequence of an ageing population.[4]

Demographic patterns might also be related to some behavioural aspects, including the increase in the use of coastal water for recreational activities or greater proportion of the population eating undercooked seafood,[4] which are intrinsically associated with the exposure to *Vibrio*. By combining population data and *Vibrio* suitability, this study identified a strong growth of population at risk in the past 40 years, rising from 610 million to 1100 million under the SSP2-4.5 scenario. The period between 1980 and 2020 corresponded with the major increase of reported *Vibrio* cases to date, particularly in those areas reported in this study with the highest risk: the north of Europe,[7,8] Atlantic northeast,[11,29] Pacific northwest,[3] and southeastern China.[30] However, and according to these projections, the growth trend will be weakened for the next decades showing a more moderate increment with a maximum around 1300 million after 2050, primarily as a consequence of the stabilisation of the world population in regions with *Vibrio* risk. Furthermore, it is possible to make an estimate based on these results of the morbidity of vibriosis on a global scale. By use of the infection rate for the USA as reference[25] and the correction for under-reporting estimated for this country,[26] it was possible to provide the first global estimation of the number of *Vibrio* infections, with current values around an estimate of a half million cases worldwide. The infection rate per 100 000 population, after correction (of about 43) for under-reporting from the USA applied for these calculations, can be considered a conservative assumption within a global context. Higher infection rates have been reported for some Asian countries with values above 100 cases per 100 000 population when population surveys and sentinel hospital surveillance were applied to overcome the bias introduced by a deficient reporting system.[31–33] The most positive outcome is that projections show that *Vibrio* morbidity will remain relatively stable over the coming decades.

This work and its projections provide key components to visualise the global changes and threat associated with *Vibrio* illness. Development and validation of these types of models will help public health policy makers to build up more robust intervention plans and anticipate responses to future scenarios of *Vibrio* risk.

Contributors

JT and JM-U conceptualised the research. JT was responsible for the collection of the original data and oversaw data collection and verified data. JT and JM-U conducted analyses, wrote the Article and provided inputs for the final draft. Both authors had full access to all data in the study and were responsible for the final decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

All data used in our research is free and open access. The Methods section provides the references to the different datasets used as inputs in our study. The intermediate and final datasets are available on request from the authors.

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