Climate Change Broadly Increases Infectious Disease Risks

Climate change could prove damaging to individual plant and animal species, to complex ecosystems, and of course to humans

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By favoring the growth of pathogens, climate change will make infectious disease outbreaks more likely and more frequent, according to researchers who gathered during the 2014 ASM General Meeting (GM), held in Boston last May. Those pathogens threaten not only food sources and human health, but also entire ecosystems, they say. Rising temperatures are a major factor in this forecast, allowing many pathogens to expand their geographic ranges and prolong seasonal risks. Higher temperatures also promote pathogen growth and virulence, particularly in *Vibrio* species that infect a wide range of marine organisms and humans. In addition, changing climate conditions can stress host plant and animal species, making them more susceptible to infections.

Taken together, they warn, climate change is tipping the balance between host and pathogen, a shift in favor of pathogens that will lead to more frequent and severe outbreaks of bacterial, viral, and fungal diseases across diverse ecosystems.

Plant Pathogens Threaten Crops along with National Economies

Climate change will affect crop yields by altering rainfall and temperatures, but also by enhancing the growth of plant pathogens, according to Caitilyn Allen of the University of Wisconsin, Madison, who spoke during the 2014 ASM GM plenary session “Global Change Microbiology: Anthropogenic Pressures and Microbial Response.” For example, rising temperatures threaten coffee tree plantations by boosting the fungal pathogen *Hemileia vastatrix*. Commonly known as coffee rust, *H. vastatrix* infiltrates the leaves of coffee trees, defoliating them and often killing the tree. However, because the fungus cannot survive below 10°C, trees planted at higher elevations have historically been safe from this blight. “Until recently, rust only appeared below 1,300 m altitude; cooler temperatures protected higher altitude plantings from the disease,” she says.

Temperatures in tropical highlands are increasing and this terrain is experiencing earlier and heavier rainfall, allowing *H. vastatrix* to grow at higher altitudes than ever before, according to Allen. Since 2012, Central America has been struck with an epidemic of coffee rust that is badly damaging trees and undercutting local coffee-dependent economies, she says. “Rust has been in the Americas for over 40 years, but never affected more than 5% of the crop. Last year’s incidence was 53%.”

This striking increase could indicate the emergence of a new, more virulent strain of *H. vastatrix*, but genetic analysis reveals that the pathogen itself has not changed, Allen continues. Instead, average temperatures increased a mere 1.5°C. “Rust was the explosive, but climate change was the detonator,” she says.

If average temperatures continue to rise by another 1–1.5°C, as expected, land suitable for coffee production will be drastically reduced, ac-
According to the Intergovernmental Panel on Climate Change. As it is, rust reduced coffee yields 20% across Central America in 2013, costing 500,000 jobs and $500 million. These losses are hitting local economies hard, with coffee as the most valuable commodity and main driver of the economy in many Latin American countries. Guatemala, Nicaragua, Honduras, and Costa Rica all declared states of emergency in 2013 due to rust-associated losses, Allen says.

While coffee rust is the first plant disease epidemic clearly attributable to global warming, others may soon follow, according to Allen. Changing weather conditions not only may favor particular plant pathogens but can also stress the host plants, making them less resilient and more vulnerable to attack. Monoculture crops, which account for much of the world food supply, are particularly susceptible to pathogens due to their lack of genetic diversity. For example, the bacterial pathogen *Xanthomonas campestris* pathovar *musacearum*, which causes wilt, is running rampant through banana plantations because the trees, which are genetically identical clones, carry no natural resistance to this pathogen. “Production losses are estimated at 53%, with $8 billion in economic costs over the past 10 years,” Allen says.

Bananas are a dietary staple in nations where food is scarce, and a driver of the economy in many developing nations. The impact of this plant pathogen could prove catastrophic, particularly if forthcoming climate changes shift the balance to favor its growth even more than it already has. “As many host-pathogen interactions are highly vulnerable to changes in environment, climate change can alter the likelihood of disease outbreaks [and] has altered terrestrial ag-

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**FIGURE 1**

Coffee leaf rust caused by the fungus *Hemileia vastatrix*. This disease has spread rapidly through growing areas previously immune to it because of rising temperatures. (Image credit: Smartse—Own work. Licensed under CC BY-SA 3.0 via Wikimedia Commons [http://commons.wikimedia.org/wiki/File:Hemileia_vastatrix_-_coffee_leaf_rust.jpg#mediaviewer/File:Hemileia_vastatrix_-_coffee_leaf_rust.jpg].)
“Agricultural disease risk,” says Colleen Burge of the University of Washington, Seattle.

**Pathogens of Fish and Shellfish Threaten Seafood Industries**

Climate change-associated outbreaks of infectious diseases attributable to marine pathogens are also on the rise, posing an increased threat to seafood industries, according to Burge, who spoke during the 2014 ASM GM symposium “Small Change, Big Change: the Growing Challenge of Climate Change in the Ocean.” Cultured and wild harvests of finfish and shellfish are affected, including salmon, abalone, bivalves, and crustaceans. “Rising sea surface temperatures have been linked with increasing levels and ranges of diseases in humans and in marine life, including corals, abalones, oysters, fishes, and marine mammals,” she says. “Climate shifts can impair the immune response of a host and increase the frequency of disease. This is especially true for ectothermic organisms such as shellfish, corals, and finfish.” Other climate-related factors contributing to these problems include ocean acidification, caused by increasing levels of dissolved carbon dioxide, as well as changes in salinity and stratification.

Finfish, including salmon and rainbow trout, are susceptible to infection by *Icthyophonus*, a protozoan species that invades muscle tissue, impairing swimming ability, which leads to death. Elevated water temperatures promote disease progression, which impairs spawning and further increases mortality rates. “In addition to its population-level effects on marine fish resources, ichthyophoniasis affects human societies by reducing the market value of fish... resulting in unsightly and aromatic lesions in the skeletal muscles of infected fish, rendering the affected fillets unmarketable,” Burge says. The fishing industries based in Alaska and Nova Scotia are being hit hardest by *Icthyophonus* outbreaks as warmer waters creep northwards.

*Vibrio* species are prevalent among the pathogens that infect and are carried by shellfish. *Vibrio harveyi*, a pathogen of many marine organisms, including prawns, lobsters, and fin fishes, is threatening the European abalone, *Haliotis tuberculata*. “Significant alterations in abalone host-bacterial parasite dynamics in recent years are associated with increased seawater temperature,” Burge says. During spawning season, increasing the seawater temperature from 17 to 18°C can tip the balance to favor *V. harveyi*, leading to 80% losses in abalone harvests, she says. Along the California coast, *Candidatus Xenohaliotis californiensis*, which infects the abalone gut and interferes with nutrient absorption, has been moving northwards, with particularly damaging outbreaks during warmer El Niño years.

Meanwhile, *Vibrio tubiashii*, a pathogen that infects larval oysters and which is linked to ocean acidification, is damaging the oyster industry along the west coast of the United States. Other oyster pathogens, such as the protozoans *Perkinsus marinus* and *Haplosporidium nelsoni*, are increasingly problematic along the east coast, moving into economically important regions such as the Chesapeake Bay. “The prevalence and intensity of these diseases are subject to influence by cyclical climate patterns, such as the El Niño–Southern Oscillation (ENSO) and North Atlantic Oscillation, which modify regional and local temperature and rainfall (salinity) conditions,” says Burge.

**Marine Vibrio Species Threaten Human Health**

Climate change and its impact on ocean conditions promote the growth of other *Vibrio* species that more directly threaten human health, according to Burge. *Vibrio parahaemolyticus*, a shellfish pathogen that causes food poisoning in humans, has expanded its range northwards in recent years, invading major seafood-producing regions such as the Chesapeake Bay and Prince William Sound in North America and the Baltic Sea in Europe. *Vibrio vulnificus*, a species that causes necrotizing wound infections, also expanded its geographic range. Regional outbreaks among humans infected with these and similar *Vibrio* species correlate with local sea surface temperatures, with the number of cases nearly doubling for every 1°C increase in the Baltic Sea, says Burge, citing work by Craig Baker-Austin of the Centre for Environment, Fisheries and Aquaculture Science in Weymouth, Dorset, United Kingdom. With warmer ocean temperatures stretching earlier into spring and later into autumn, seasonal risk has expanded as well.

“Pathogenic *Vibrio* bacteria pose a significant human health risk,” Burge says. “In the United States alone, there are approximately
4,600 cases of *Vibrio* infection each year, of which approximately 90 are *V. vulnificus* cases and 4,500 are *V. parahaemolyticus* cases.” These highly invasive pathogens can cause septicemia and death.

Warming temperatures and changes in rainfall can also make the environment more hospitable for *Vibrio cholerae* growth, and can lead to increases in human infections, according to Rita Colwell of the University of Maryland, College Park. “Cholera outbreaks have been linked to environmental and climate variables including precipitation, flooding, river levels, sea surface temperatures, and coastal salinity,” she says. Warm air temperatures combined with springtime drought, which increases water salinity in estuaries, provide optimal conditions for *V. cholerae* growth, setting the stage for outbreaks when rains come. “Heavy rainfall, followed by inundation and destruction of sanitation infrastructure, accelerates interactions between contaminated water and human activities, resulting in an epidemic,” she says. Rising global temperatures and more extreme weather patterns can result in more droughts and flooding, suggesting cholera outbreaks could increase in frequency and intensity.

From data collected for 26 years from northern India, Colwell generated climate-based early warning systems to identify high-risk areas and to predict cholera outbreaks months ahead of time. "Location and intensity of cholera outbreaks can be predicted up to 3 months in advance in the Bengal Delta region with understanding of underlying hydroclimatology and satellite-derived environmental variables," she says. Other, similar models help to predict such outbreaks in Mozambique, Pakistan, and Haiti, giving those communities and governments time to prepare for outbreaks, with the goal of reducing the cholera disease burden and related deaths, she says.

*FIGURE 2*

Scaning electron micrograph (SEM) of a *Vibrio vulnificus* bacterium. *V. vulnificus* is among several *Vibrio* species that have expanded their geographic ranges due to increasing seawater temperatures. *V. vulnificus* causes necrotizing infections in wounds that are exposed to contaminated seawater. (Centers for Disease Control and Prevention image.)
Marine Pathogens Disrupt Important Ecosystems

Marine bacterial pathogens, particularly *Vibrio* species, can disrupt ecosystems by infecting species that provide essential functions within those communities. For example, oysters help to maintain reef habitats, filter water, and serve as food sources for other organisms within such ecosystems. "Hence, in addition to being economically devastating, oyster diseases affect overall ecosystem productivity and health," says Burge. Terrestrial examples of species-specific diseases disrupting forests include Dutch elm disease and chestnut blight. Although such cases of infectious disease-driven ecosystem restructuring are well documented, researchers are only beginning to understand how climate-associated infectious diseases affect marine ecosystem dynamics.

Coral reefs appear to be the hardest hit so far for a number of reasons, according to Colwell. "Coral reefs, in particular, are already experiencing unprecedented degradation worldwide due in part to infectious disease outbreaks and bleaching episodes that are exacerbated by increasing sea-surface temperatures," she says. *Vibrio* species are causing mass mortalities in coral species throughout the Mediterranean, while yellow band disease, also caused by *Vibrio* spp., threatens corals in the Caribbean and Pacific. "*Vibrio coralliilyticus*, a globally distributed bacterium associated with multiple coral diseases, infects corals at temperatures above 27°C," she says. Further contributing to the problem, at higher temperatures virulence factors that affect motility, host degradation, secretion, antimicrobial resistance, and transcriptional regulation are up-regulated.

*V. coralliilyticus* also takes advantage of climate-stressed, immune-compromised corals, responding to stress signals that they emit, according to Roman Stocker, Melissa Garen, and their colleagues of the Massachusetts Institute of Technology in Cambridge. In response to heat stress, some corals secrete dimethylsulfoniopropionate (DMSP), a chemical that attracts *V. coralliilyti- cus*. "In heat-stressed coral fragments, DMSP concentrations increase fivefold and the pathogen’s chemotactic response was correspondingly enhanced," says Stocker.

Corals are highly sensitive to climate-change stress due to their reliance on microbial symbionts, namely dinoflagellates of the genus *Symbio- dinium*. In nutrient-poor tropical waters, corals rely on carbon-containing nutrients generated by these photosynthetic algae. "*Symbiodinium* trap solar energy and nutrients, providing more than 95% of the metabolic requirements of the coral host," says Ove Hoegh-Guldberg of the University of Queensland, Australia, who spoke during the 2014 ASM GM session “Microbes in Symbiosis, Signaling and at Sea.”

However, these symbionts are compromised by both ocean acidification and rising ocean temperatures, Hoegh-Guldberg continues. "Coraline algae are among the most sensitive calcifying organisms to ocean acidification as a result of increased atmospheric carbon dioxide," he says. "Under high carbon dioxide conditions, corals at the phenotype level lost over half their *Symbiodinium* populations, and had a decrease in both photosynthesis and respiration."

Rising temperatures make matters worse; increases of only 1–2°C in water temperature further disrupts symbiosis, according to Hoegh-Guldberg. "Previous experiments that focused on ocean acidification alone may have underestimated the impact of future conditions on coraline algae," he says. "Given the central role that coralline algae play within coral reefs, these conclusions have serious ramifications for the integrity of coral reef ecosystems."

Loss of algal symbionts, which leads to bleaching, leaves corals struggling for survival and highly susceptible to infectious disease. "Over the past four decades, increasing environmental stress from rapidly changing climate . . . has disrupted the balance between hosts, agents, and the environment that underpins coral health," Burge says. "Disruption of coral-microbial symbioses and concomitant reduced resistance to opportunistic pathogens have been major factors in the deterioration of coral reef communities worldwide."

Overall, higher ocean temperatures and acidification favor pathogens, resulting in more frequent and severe outbreaks of infectious diseases in corals across the globe, according to Burge. "The host range and abundance of one of the most temperature- and nutrient-sensitive coral diseases, black band disease, have increased worldwide, likely reflecting the combined impacts of compromised host resistance and enhanced pathogen virulence associated with increasing seawater temperature and declining water quality," she says.
Other temperature-dependent coral diseases include white syndrome, white patch disease, white plague, and yellow band disease, responsible for decimating coral populations in the Caribbean, Mediterranean, and Indo-Pacific regions. While some corals recover from these outbreaks, their resilience is being tested by continuing warming trends that do not provide adequate recovery time between heat stresses, according to Hoegh-Guldberg. Thus, 50% of corals in the Great Barrier Reef have disappeared since bleaching events began several decades ago. Similarly alarming statistics are reported for the Caribbean and other tropical reef regions.

The loss of coral reefs and other marine ecosystems can have far-reaching impacts, according to Burge. “Marine ecosystems are among the most valuable and heavily used natural systems worldwide and provide critical ecosystem services, including shoreline protection, water filtration, nursery grounds, food from fisheries and aquaculture, and revenue from tourism,” she says. Hoegh-Gulberg adds, “Climate change and ocean acidification are already . . . threatening the ability of the oceans to continue providing economic resources and environmental services on which we so critically depend.”