Climate Change and Medical Mycology

Sarah Sedik, MSc[a,b], Matthias Egger, MD[a,b,c], Martin Hoenigl, MD, FECMM, FIDSA[a,b,c,*]

KEYWORDS

• Fungal infections • Climate change • Natural disasters • Medical mycology

KEY POINTS

- *New fungal pathogens emerging:* Fungal species adapt to a warmer climate by developing thermotolerance, resulting in the emergence of new fungal pathogens that can survive at human body temperature.
- *Antifungal Resistance:* Climate change exacerbates antifungal resistance by triggering increased virulence in fungal pathogens, necessitating increased utilization of fungicides in agriculture.
- *Geographic Expansion:* Warmer temperatures and altered precipitation expand the geographic range of fungal diseases like Valley fever, histoplasmosis, and blastomycosis.
- *Impact of Natural Disasters:* Climate change-driven natural disasters, such as floods and wildfires, facilitate fungal spore dispersal, and increase infection risks through environmental and traumatic exposures.
- *Inequality is rising:* Climate change exacerbates inequalities and social determinants of health resulting in a disproportionate impact on fungal diseases.

INTRODUCTION

Climate change, one of the most pressing issues of the 21st century, has far-reaching impacts on various facets of life, including public health.[1] While much attention has been given to the effects of climate change on physical health through heatwaves, vector-borne diseases, and natural disasters, an emerging area of concern is its influence on medical mycology.[2–4] Medical mycology, the study of fungi that cause diseases in humans, is gaining importance as climate change alters the ecosystems where these fungi thrive.[5] Shifts in temperature, humidity, and weather patterns create

[a] Division of Infectious Diseases, Department of Internal Medicine, Medical University of Graz, ECMM Excellence Center, Auenbruggerplatz 15, Graz 8036, Austria; [b] Translational Mycology, Medical University of Graz, Graz, Austria; [c] BioTechMed-Graz, Graz, Austria
* Corresponding author. Division of Infectious Diseases, Department of Internal Medicine, Medical University of Graz, ECMM Excellence Center, Auenbruggerplatz 15, Graz 8036, Austria.
E-mail address: hoeniglmartin@gmail.com
Twitter: @SarahSedik (S.S.); @MatthiasEgger11 (M.E.); @martinhoenigl (M.H.)

Infect Dis Clin N Am 39 (2025) 1–22
https://doi.org/10.1016/j.idc.2024.11.002 id.theclinics.com

new niches for pathogenic fungi, enhance their virulence, and expand their geographic range, posing significant challenges to health care systems globally.[6]

Fungi, despite their ecological roles, present substantial health risks to humans. Climate change is accelerating the adaptation of fungi to warmer temperatures and changing environmental conditions. This phenomenon has led to the emergence of more aggressive strains like *Candida auris* and *Cryptococcus deuterogattii*, which can tolerate higher temperatures and human body heat and now pose a growing threat to global health.[6–8] Moreover, climate change contributes to more frequent and severe extreme weather events such as hurricanes, floods, and wildfires, which can disrupt ecosystems and human habitats, increasing exposure to fungal spores.[8–10] Post-disaster environments, such as those seen after the Indian Ocean tsunami, the Joplin tornado, and Hurricane Katrina, have been linked to outbreaks of fungal infections like mucormycosis due to trauma and increased exposure to fungal spores.[11–13] Climate change also affects the epidemiology of endemic fungal diseases such as coccidioidomycosis and histoplasmosis in terms of expanding the range of fungal pathogens affecting animals and plants, posing a threat to global food security.[9] These environmental changes may also weaken human immune responses, making populations more susceptible to fungal infections.[5,9,14] Mechanisms are summarized in **Fig. 1**.

In this review, we delve into the complex interaction between climate change and medical mycology. We explore how climate-induced environmental shifts are reshaping the epidemiology of fungal diseases, leading to the emergence of resilient and more pathogenic strains and altering geographic distributions. Additionally, we discuss strategies to mitigate these escalating health risks. We aim to offer insights into the intrinsic relationship between climate change, fungal ecology, and human health, underscoring the urgency for proactive measures to tackle these emerging challenges.

HEAT STRESS AS A DRIVER OF FUNGAL THERMOTOLERANCE

Fungal pathogens are adapting to rising temperatures driven by climate change, becoming more thermotolerant and expanding their reach.[9,15] Thermotolerance, the ability of fungi to survive at higher temperatures, may result in adaption to the human body temperature.[16] Fungal pathogens that are currently not a threat to mammals may thereby learn to survive at high temperatures facilitating fungal disease in humans. Heat stress, such as from mammalian body temperature, can induce hypermutation

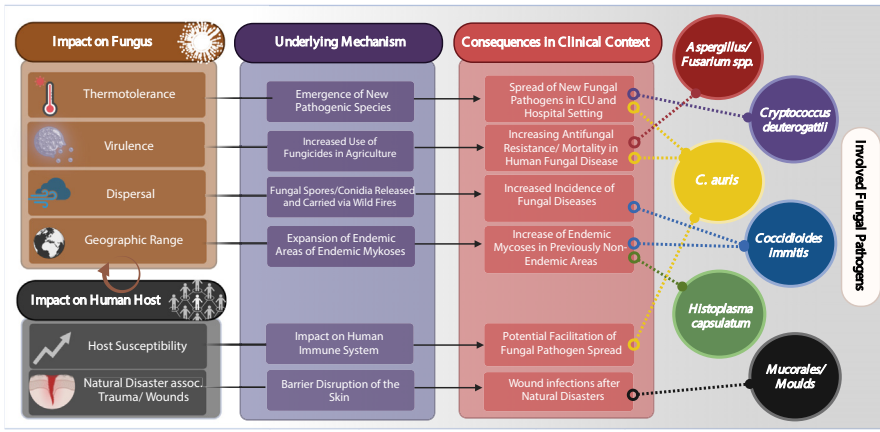

Fig. 1. The impact of climate change on the fungus and the host and the consequences in the clinical context.

in fungal pathogens, leading to the development of hypervirulent and drug-resistant mutants as was recently shown for *Rhodosporidiobolus fluvialis*.[17] Studying the cellular mechanisms of pathogenicity is essential as the number of serious mycoses rises, posing a growing public health challenge.[16] Fungi employ various mechanisms to enhance thermotolerance in response to rising temperatures. Key adaptations include the synthesis of heat shock proteins (HSPs) such as HSP70 and HSP90, which assist in protein folding and stability under heat stress.[18] Additionally, fungi accumulate compatible solutes like trehalose and glycerol, which respectively stabilize proteins and membranes against thermal denaturation. Membrane composition alterations help maintain crucial fluidity at elevated temperatures. Moreover, fungi utilize antioxidant systems to counteract oxidative stress induced by heat, thereby preserving cellular integrity.[18]

The emergence of new species causing disease in humans, such as *C. orthopsilosis* or *Cryptococcus deuterogattii* is a prominent example of these mechanisms.[6] *Cryptococcus deuterogattii*, a member of the *C. gattii* complex, notoriously exhibit heightened thermotolerance compared to other members of its group.[19] It is increasingly recognized as a pathogen affecting both humans and animals, with recent occurrences observed in British Columbia, Canada, and the states of Washington and Oregon in the United States (US).[20] Climate change is also hypothesized acting as a contributing factor to the emergence of *C. auris*, potentially enabling its adaptation to mammalian temperatures by reducing the thermal restriction zone between environmental and mammalian habitats.[21] *C. auris* and *C. orthopsilosis* have thereby transformed from a non-threatening environmental organism to a formidable human pathogen.[6,9,22,23] Hypotheses underscore that global warming may facilitate the emergence of new fungal diseases by altering environmental conditions favorable to fungal evolution and adaptation, while various other factors played a role in *C. auris* becoming a human pathogen.[21] Details and examples on how development of thermotolerance has contributed to disease in humans are outlined in **Table 1**. Various non-pathogenic fungi grow at 37°C, suggesting body temperature alone does not prevent infections. While thermotolerance is important, it is solely one component of the multifaceted fungal pathogenicity. *C auris*, as a notable example, has also developed azole resistance, potentially due to exposure to agricultural chemicals, as outlined further as follows.[16]

Global warming and increase in marine water temperatures might have acted as a selection force for thermotolerant hybrids of *C. orthopsilosis* characterized by fitness advantage compared to parental strains. These hybrids are found in both, warming marine ecosystems but also cases of human infections, likely outlining that climate change has contributed to the emergence of *C. orthopsilosis* as a human pathogen.[23,24]

CLIMATE CHANGE ASSOCIATED STRESS COMES IN MULTIPLES AND TRIGGERS INCREASING FUNGAL VIRULENCE: IMPACTS ON HEALTH, AGRICULTURE, AND FOOD SECURITY

Virulence, the ability of a pathogen to cause disease in a host, is a crucial aspect of medical mycology that meets with the evolving challenges of climate change. As global temperatures rise and weather patterns become more unpredictable, the dynamics of fungal infections and their virulence are being increasingly influenced.[6] Climate change does not only result in heat stress and thermotolerance but also poses concomitant stress due to increased ultraviolet (UV) light exposure, water stress, limited nutrition, and so forth, which results in increased virulence. In addition to the thermotolerance mechanisms described earlier, fungi adapt to those stress factors

Table 1
Examples from the literature on the impact of climate change on fungal disease in humans

Impact of Climate Change	Fungal Pathogen Involved	Mechanism	Clinical Impact	Year of First Occurrence	Reference
Thermotolerance	*Candida auris*	Heat shock proteins, stress response pathways, and a robust cell wall, along with urbanization and rural development, likely drove the development of thermotolerance and the emergence of a new human fungal pathogen.	Over the past 15 y, *C. auris* has spread to over 41 countries, infecting 13 million people and causing 1.5 million deaths annually.	2009	21,85–87
	Cryptococcus deuterogattii	Spread is driven by human activities like vehicle movement, footwear, construction, forestry, and water dispersal, as well as potentially by climate change. It is mediated by calcineurin signaling, heat shock proteins, cell membrane adaptations, and cell wall remodeling.	Thermotolerance enhances the pathogens virulence, enabling it to cause severe infections in healthy individuals and contributing to widespread outbreaks.	2016	6,19
	Candida orthopsilosis	Hybrids characterized by increased thermotolerance and advantage of fitness over parental strains are found in both warming marine ecosystems and as causative pathogens of human infections.	Thermotolerance driven by climate change has likely contributed to the emergence of this new human fungal pathogen,	2008	23,88

Virulence	*Rhizopus arrhizus and Mucor circinelloides*	NMM worsens with the TSC due to increased virulence from soluble factors.	NMM under TSC is associated with increased severity and mortality but targeted therapies like topical calcineurin inhibitors could improve treatment.	2020	[77]
	Puccinia striiformis	*Puccinia striiformis f. sp. Tritici* causing stripe rust increased virulence under warmer and dryer conditions, caused significant grain loss and quality reduction, threatening South African wheat production.	Increased use of fungicides in agriculture to tackle the threat, resulting in an increased threat of environmental resistance.	1996	[6,89]
	Fusarium graminearum	Thriving in warm, humid conditions, is replacing *F. culmorum* in temperate regions, and leading to significant crop yield losses.	Increased mycotoxin contamination in food and animal feed, posing health risks to humans and animals.	1999	[6,90,91]
Resistance	*Aspergillus fumigatus*	Environmental azole resistance arises due to mutations in the cyp51A gene, which complicates treatment and links environmental fungicide use and climate change to heightened clinical resistance.	Resistance complicates treatment due to mold-active azoles like voriconazole, isavuconazole, and posaconazole. Linked to agricultural azole use and occurs even in untreated patients.	2011	[31,32,39,92–94]
	Candida auris	Resistance is influenced by agricultural fungicides and environmental factors, leading to mechanisms like ERG11 overexpression and efflux pumps.	The emergence of multidrug-resistant strains like *C. auris*, complicating treatment.	2009	[42]

(*continued on next page*)

Table 1
(*continued*)

Impact of Climate Change	Fungal Pathogen Involved	Mechanism	Clinical Impact	Year of First Occurrence	Reference
	Cryptococcus deuterogattii	Cross-resistance to clinical azoles due to environmental fungicides, affecting virulence factors like capsule size.	Complicates treatment and increases disease severity, especially in immunocompromised individuals.	2016	[39]
	Rhodosporidiobolus fluvialis	It increases antifungal resistance due to heat-induced mutations, driven by reactive oxygen species.	Recently identified as a human pathogen. Research from 2009 to 2019 found *R. fluvialis* in deceased patients, underscoring its severity. Causes severe infections in immunocompromised individuals.	2024	[14,95,96]
Geographic spread	*Histoplasma capsulatum*	Increasingly recognized in Europe, suggesting a broader geographic distribution.	Increasing number of autochthonous cases reported Europe and Israel, and increasing number of cases reported from China.	2001	[53,54]
	Coccidioides immitis	Climate change is causing significant shifts in the geographic range and incidence of Valley fever, facilitating the spread into historically unaffected areas.	Autochthonously acquired Valley fever cases now reported from many states in Western US, including Washington and Oregon.	2000	[10,52,69,97]

Dispersal	*Coccidioides immitis*	Dispersal of spores via wildfire smoke to costal metropolitans of California.	Increased rates of clinical presentations/new diagnoses of coccidioidomycosis in the months following wildfire smoke exposure	2021	[57,98,99]
Host susceptibility	*Candida auris*	*C.auris* in the USA shows genetic links to isolates from South Asia, South America, Africa, and East Asia. The introduction appears to have occurred multiple times, with some cases linked to international travel.	Worldwide spread of *C. auris* facilitated by worldwide travel and migration.	2014–2018	[64]
Natural Disaster	*Mucorales species*	Rise in mucormycosis cases following the Indian Ocean tsunami in 2014.	Increased severe infections, particularly in immunocompromised individuals and those with traumatic injuries, including wound contamination and post-disaster skin and soft tissue infections.	2014	[9,100]
	Mold infections *(*eg, *Aspergillus, Mucorales, Fusarium, and Scedosporium taxa)*	Increased spore dispersal and infection rates following natural disasters (eg, Hurricane Katrina).	Higher incidence of fungal infections post-disaster.	2005	[79,82]

by enhancing detoxifying enzyme production, modifying cell walls, increasing melanin production, broadening nutrient utilization, enhancing virulence and immune evasion, and developing greater resistance to oxidative stress, pH changes, UV radiation, and antifungal drugs.[9] They also demonstrate increased biofilm formation and exhibit changes in dimorphism.[9,25] These adaptions result in increasing virulence, influencing agricultural practices and potentially contributing to antifungal resistance, posing significant challenges for both human health and agriculture under the One Health framework.[9]

Puccinia striiformis, or rust fungus, causing wheat stripe rust, has adapted to warmer climates since 2000 with aggressive strains like Pst1, Pst2, and "Warrier" replacing older ones. This has led to major outbreaks in regions such as the southern US and Australia. Meanwhile, *Fusarium graminearum*, favoring warm, humid conditions, has increasingly replaced *F. culmorum* in temperate areas, causing significant yield losses and raising concerns about mycotoxin contamination in food and animal feed[6] (see **Table 1**).

The proliferation of these virulent fungal strains has direct implications for global food security. Crop losses due to fungal infections not only threaten local economies but may also contribute to global food scarcity. Virulent fungi significantly threaten global food security by destroying up to 30% of crops and producing harmful mycotoxins, which compromise food safety. The increasing virulence of these fungi, exacerbated by climate change and population growth, necessitates innovative and interdisciplinary research for effective control, especially for vulnerable and low-income populations.[26]

CONSEQUENCES OF CLIMATE CHANGE ASSOCIATED STRESS—ANTIFUNGAL RESISTANCE IN A CHANGING CLIMATE AND AGRICULTURAL LANDSCAPE

Antifungal resistance is a growing concern potentially exacerbated by climate change, affecting the prevalence and severity of fungal infections. Rising temperatures and altered precipitation patterns create ecological niches favoring fungal growth and transmission. This environmental shift also affects fungal virulence and hence resistance mechanisms, challenging treatment efficacy and complicating disease management. For example, a recent study has identified *Rhodosporidiobolus fluvialis* (see **Table 1**) as a new fungal pathogen that exhibits increased mutation rates and drug resistance when exposed to higher temperatures.[17] It has caused fatalities in the United Kingdom, marking its first detection in humans. Thriving in warm temperatures, this fungus has developed resistance to antifungal drugs (see **Fig. 1**).

Fungal diseases account for 80% of plant health issues, resulting in $100 to 200 billion in annual losses.[27] Climate change may further exacerbate agricultural fungal threats, leading to significant crop losses and economic costs.[28,29] Countering this threat by the increased use of fungicides[30–32] and its consequences such as environmental pollution are important drivers of antifungal resistance.[9,15] Fungicides are essential for food security but face resistance challenges, highlighted since the 1960s.[33] Cross-resistance concerns arise as some fungicides share mechanisms with human and animal antifungals, particularly azoles.[34,35] These fungicides are extensively applied to crops to combat phytopathogens, ensuring plant health and productivity. However, the pervasive environmental presence of azoles creates selective pressure that promotes the evolution of resistant strains of *Aspergillus*.[36] In *A. fumigatus* (see **Table 1**), resistance typically arises from mutations in the cyp51A gene, severely complicating the treatment of these infections due to resistance to mold-active azoles like voriconazole, isavuconazole, and posaconazole, the only

oral antifungals currently available for treatment of aspergillosis.[37] This genetic alteration has been identified in environmental samples from soil, compost, and plants, as well as in clinical isolates from patients with no history of azole therapy, highlighting a clear link between farming practices and clinical treatment failures.[31,32,38,39]

In the Netherlands, invasive aspergillosis caused by multi-azole-resistant *A. fumigatus* has increased since 1999, affecting 6.0% to 12.8% of patients, primarily due to the TR/L98H mutation in the cyp51A gene, found in over 90% of clinical isolates. This resistance mechanism is linked to the exposure to environmental azole compounds with resistant isolates also detected in soil and compost.[40] Tulip bulbs imported from the Netherlands were surveyed for azole-resistant *A fumigatus* (ARAf), revealing contamination rates ranging from 6.3% to 15.8% attributable to a tandem-repeat mutation in the cyp51A gene promoter. The application of fungicides such as benomyl or prochloraz was shown to successfully lower the incidence of ARAf isolation, representing a novel approach to addressing human fungal pathogen presence in plant bulbs.[41]

Widespread azole use poses a potential risk for resistance in other fungal pathogens like *Candida* spp. (see **Table 1**), which can develop resistance mechanisms such as ERG11 overexpression and efflux pumps, influenced by agricultural fungicides. The emergence of multidrug-resistant strains, such as *C. auris*, is particularly concerning due to its resistance to fluconazole in over 90% of isolates, alongside varying resistance to other antifungal drugs like amphotericin B and echinocandins. Although novel antifungals like SCY-078 yield clinical activity, further research is essential to understand resistance mechanisms in *C. auris*.[42] The emergence of *C. auris* as a drug-resistant pathogen cannot be solely attributed to antifungal drug selection pressures, as similar resistance patterns existed in other fungal species before *C. auris* appeared.

Sexual reproduction in *Candida* spp. enhances genetic diversity and potential resistance mechanisms, influenced by agricultural fungicides altering virulence. Similarly, *Cryptococcus* spp. (see **Table 1**), commonly associated with trees, develop cross-resistance to clinical azoles due to environmental fungicides, affecting critical virulence factors like capsule size. The acquisition and expression of resistance in these fungi vary with temperature changes, affecting disease severity.[39]

Rhodosporidiobolus fluvialis, which primarily affects immunocompromised individuals, is notably resistant to fluconazole and caspofungin, and can rapidly develop resistance to amphotericin B at 37°C, resulting in strains that are resistant to all three major antifungal drugs. The heat-induced mutations are driven by reactive oxygen species and lead to the emergence of more virulent, pseudohyphal variants. These findings demonstrate that this new fungal pathogen increases mutation rates and resistance in response to elevated temperatures.[17]

Antifungal resistance in *Fusarium* spp. presents a current clinical challenge, particularly in the context of invasive infections involving the central nervous system (CNS).[43] While rare, *Fusarium* spp. exhibit intrinsic resistance to echinocandins and often have elevated minimum inhibitory concentrations to triazoles and polyenes, potentially driven by antifungal use in the clinics and the environment. This resistance complicates treatment strategies, with historic cases primarily treated with amphotericin B before the approval of voriconazole. Recent guidelines recommend lipid formulations of amphotericin B or voriconazole monotherapy as first-line treatments, sometimes combined to broaden antifungal activity.[44] Emerging therapies such as fosmanogepix and olorofim may offer promising alternatives due to their ability to penetrate the CNS effectively and combat resistance mechanisms seen in *Fusarium* species.[43]

The dual usage fosters azole resistance in pathogens like *Aspergillus, Fusarium,* and *Candida*, highlighting the urgent need for new antifungal classes for humans but also fungicides. Olorofim and fosmanogepix are the first drugs of two entirely new classes

of antifungals with novel mechanisms of action, that are currently in clinical development. However, fungicides from the same new drug classes, and thereby sharing mechanisms of action, are developed simultaneously with much faster pathways to approval, risking cross-resistance.[31] The new fungicides ipflufenoquin and quinofumelin, which target the enzyme dihydroorotate dehydrogenase, share their mechanism with olorofim, a promising antifungal drug.[45,46] Cross-resistance between these compounds has been observed, raising concerns about their impact on medical treatments. Fosmanogepix, another antifungal drug in trials, targets the glycosylphosphatidylinositol-anchored wall transfer protein essential for fungal cell walls.[47,48] The potential for cross-resistance with aminopyrifen, a similar agricultural fungicide, needs further study to ensure the efficacy of medical treatments is not compromised.[49]

US regulatory agencies are developing frameworks to assess the risks posed by agricultural fungicides to medical antifungals, aiming to balance agricultural needs with human and animal health. This multidisciplinary effort seeks to prevent antifungal-resistant infections while maintaining effective treatments across sectors.[50]

CLIMATE CHANGE AND EXPANDING FUNGAL DISEASE GEOGRAPHIC RANGES

As global temperatures rise, areas that were previously too cold for certain fungi may become suitable habitats. This could lead to the expansion of fungal species into new geographic regions. For instance, the fungus responsible for Valley fever, *Coccidioides*, typically thrives in hot, arid regions and is commonly found in the southwestern US, Mexico, and parts of Central and South America. However, documented presence of this fungus in Washington was reported in 2015.[10]

Valley fever is officially reported in certain states, with annual cases ranging from 10,000 to 20,000 in the US. Most cases are found in California and Arizona, especially among individuals aged 60 and above. However, thousands of cases go unreported, and many are either undiagnosed or misdiagnosed.[51] Climate change is causing significant shifts in the geographic range and incidence of Valley fever in the US Projections under the RCP4.5 and RCP8.5 scenarios indicates a notable expansion of Valley fever endemic areas from the southwestern US into the Great Plains by the end of the 21st century. This expansion is driven by increasing temperatures pushing the disease-conducive climate northward. The rain shadow effect of the Rocky Mountains plays a critical role, facilitating the spread into historically unaffected areas. Agricultural activities in these regions are expected to enhance dust exposure, increasing human susceptibility.[52]

The projected increase in Valley fever cases is compounded by climate-driven factors such as drought intensification and altered precipitation patterns. Hospitalization costs are projected to rise significantly due to increased disease burden, highlighting the escalating economic impact. Improved mapping and surveillance of *Coccidioides* spp. are essential for refining predictive models and understanding disease dynamics under changing environmental conditions. The global context of Valley fever extends beyond the US, necessitating international collaboration for comprehensive surveillance and mitigation strategies. Integrating Valley fever projections into future climate assessments is crucial for informing public health policies and preparedness efforts against the expanding threat posed by this fungal disease.[52]

Changes in the environment might also expand the geographic range where fungi causing blastomycosis and histoplasmosis can survive. This phenomenon extends to fungi that are typically found in tropical or subtropical climates, such as *C. gattii*.[10]

Histoplasmosis (see **Table 1**), a fungal infection typically acquired by inhaling spores in contaminated soil, historically prevalent in the Americas and parts of Asia, is increasingly recognized in Europe, suggesting a broader geographic

distribution. A systematic review from 2005 to 2020 identified 728 cases in Europe and Israel, mostly imported from Central and South America, with 7 autochthonous cases reported.[53] Progressive disseminated histoplasmosis was prevalent among immunocompromised patients, with a mortality rate of 32% in non-human immunodeficiency virus cases.[53] In China, histoplasmosis diagnoses have risen notably from 2012 to 2022, with cases increasingly reported in southern provinces.[54] Additionally, a study of animal histoplasmosis in Europe highlighted 39 cases from 1968 to 2022, primarily affecting cats and badgers in Central Europe, with molecular analysis suggesting a distinct Eurasian clade.[55]

Emerging fungal diseases associated with animals caused by dermatophytes, *Histoplasma*, *Sporothrix*, and *Talaromyces marneffei*, pose significant threats to public health due to their capacity to infect humans through direct or indirect contact with animal reservoirs. These fungi can cause severe systemic infections in immunocompromised individuals and have the potential to evolve and exploit new hosts, potentially leading to outbreaks. Human activities such as urbanization, deforestation, and climate change contribute to increased transmission of these virulent fungi from wildlife and domesticated animals to humans.

CLIMATE CHANGE AND THE DISPERSAL DYNAMICS OF FUNGAL PATHOGENS

Climate change has the potential to alter the distribution and abundance of fungal pathogens by influencing environmental conditions such as temperature, humidity, and precipitation. These changes directly influence the dispersal mechanisms of fungal spores, resulting in shifts in pathogen geographic ranges and potentially increasing fungal infections in new regions.[9,15,21,56]

Strong winds and structural destruction facilitate the airborne spread of spores, leading to respiratory fungal infections through inhalation. Additionally, phenomena such as wildfires and volcanic eruptions release particles laden with fungal spores, dispersing them over vast distances.[9] For example, California saw increased coccidioidomycosis (see **Table 1**) admissions following wildfire smoke exposure between 2014 and 2018.[57]

Environmental disruptions also play a critical role in fungal dispersal. Activities ranging from small-scale excavation to large-scale natural disasters like earthquakes and tsunamis can significantly alter fungal habitats, leading to clusters of respiratory, cutaneous, or other fungal diseases.[8]

Even climate change itself plays a crucial role in fungal dispersal. Minor changes in temperature, moisture, and wind patterns can affect fungal spread.[8] Atmospheric transport is one of the key factors in fungal pathogen dispersal. Wind currents can carry spores over long distances, enabling them to colonize new habitats and infect susceptible hosts. Changes in wind patterns due to climate change may facilitate the long-distance spread of fungal spores, reaching areas previously unaffected by certain infections.[58,59]

Human activities such as travel and trade also contribute to fungal pathogen dispersal. Globalization has led to the movement of people, animals, and goods across borders, providing opportunities for the unintentional introduction of fungal species into new environments. As climate change continues to exacerbate the spread of infectious diseases, it is essential to consider the role of human-mediated dispersal in shaping the epidemiology of fungal infections.[60,61]

CLIMATE CHANGE AND HOST SUSCEPTIBILITY TO FUNGAL DISEASES

Host susceptibility to pathogenic fungi (see **Table 1**) is increasingly influenced by climate change and various anthropogenic factors.

Several key aspects contribute to this heightened vulnerability.[9] Increased UV light exposure weakens the human immune system by affecting T-cell function, cytokine production, and complement activation.[9,62] Secondly, the average body temperature in the US has been declining by 0.03°C per decade since the Industrial Revolution. This reduction in body temperature could narrow the thermal gap between humans and fungi, increasing susceptibility to fungal infections.[9,63]

Urbanization and enhanced global connectivity facilitate the spread of these infections while rising global travel and medical tourism contribute to the dissemination of fungi like *C. auris* and CNS fusariosis.[43,64] Climate change-driven migration exacerbates this issue, as displaced individuals often face poor living conditions, lack of clean water, and limited health care access in refugee camps, increasing their vulnerability to fungal infections.[65,66] Migrants are particularly at risk due to factors such as sexual violence, exploitation, and inadequate preventative care. Additionally, climate-induced displacement can lead to conflict and the destruction of infrastructure, further exposing individuals to fungal infections.[9]

Moreover, seasonal influences on meteorologic conditions and changes in warming patterns, along with alterations in light-dark cycles, melatonin secretion, and potential disruptions in circadian rhythms, also affect host susceptibility. These changes can affect immune responses, the expression of epithelial receptors, and the characteristics of mucosal surfaces, further heightening vulnerability to fungal infections.[9,67] Climate change-induced threats to food security can also lead to malnutrition, particularly in children, which weakens the immune system and increases susceptibility to fungal diseases.[9]

Lastly, urbanization contributes to this issue through the urban heat island effect, where higher temperatures in densely populated areas exert evolutionary pressure on microorganisms. This enhances fungal stress adaptation and potentially increases human exposure to pathogenic fungi.[9,68]

Importantly, there is a strong interplay between social determinants of health and host susceptibility to fungal diseases, and both factors are heavily impacted by climate change.[69–71] Thereby climate change is further contributing to the disproportionate impact of fungal disease, particularly affecting socially vulnerable populations and those residing in low- and middle-income countries, where resources to diagnose and treat fungal diseases are limited[9,72,73] (**Fig. 2**).

CLIMATE CHANGE AND THE INCREASE OF NATURAL DISASTERS RESULTING IN TRAUMA/WOUNDS AND FUNGAL OUTBREAKS

Natural disasters linked to climate change have significantly increased in recent decades. Between 1980 to 1999 and 2000 to 2019, reported extreme weather events nearly doubled, increasing from 4212 to 7348. The number of associated deaths slightly rose from 1.19 million to 1.23 million, while the number of people affected by these events grew from 3.25 billion to 4.03 billion. Economic losses surged dramatically, escalating from $1.63 trillion to $2.97 trillion.[74]

Natural disasters, such as floods, hurricanes, and wildfires, are increasingly exacerbated by climate change, oftentimes creating chaotic and destructive environments significantly affecting human and environmental sanity.[8,75] Optimal fungal growth and disease development occur at temperatures between 15°C and 40°C, whereas low humidity and extreme temperatures hinder both growth and spore germination. Research on plant pathogens indicates that fungal prevalence varies by habitat and season, increasing with moisture levels and decreasing with temperature due to the vulnerability of the fungi to water loss given their high surface-to-volume ratio.[76]

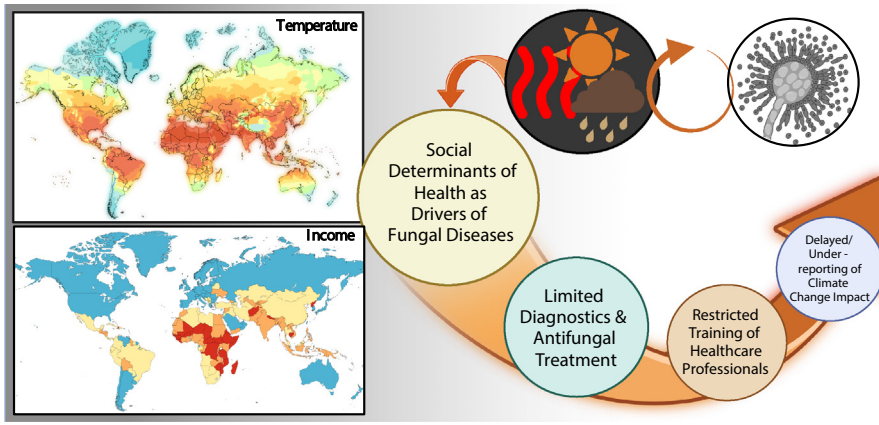

Fig. 2. Climate change exacerbates inequalities and social determinants of health resulting in a disproportionate impact on fungal diseases. Note: *Map lines delineate study areas and do not necessarily depict accepted national boundaries*.

Natural disasters create conditions conducive to fungal growth or exposure that would not exist otherwise. Events like floods create moist environments, which are essential for fungal spore germination and infection and may result in rapid growth and spread of mold fungi, dispersing fungal spores and mycotoxins over large areas,[7,8,76] and leading to mold proliferation in flooded homes and buildings.[9,10] Disasters like tsunamis increase humidity and damage buildings, promoting fungal germination. Tsunamis can also introduce waterborne pathogens like *C. gattii* to new regions.[9] Traumatic injuries and disrupted skin barriers from disasters allow entry for fungal pathogens (see **Table 1**). During the 2004 Indian Ocean tsunami, several instances of post-disaster soft tissue mucormycosis were observed, particularly among those wounded.[8,12,13] Another study investigated a cluster of cutaneous mucormycosis cases among individuals injured during the 2011 Joplin, Missouri tornado, identifying 13 patients with significant morbidity and a 38% mortality rate. The infections were linked to penetrating trauma and multiple wounds, with all cases involving the fungal species *Apophysomyces trapeziformis*.[11] Necrotizing myocutaneous mucormycosis (NMM), a trauma-related condition posing substantial mortality risks for combat and disaster victims exhibits a hypervirulent phenotype in *Mucorales* spp. (see **Table 1**) under conditions induced by tornadic shear challenge (TSC), such as magnetic stirring. TSC heightens virulence through the release of soluble factors, independent of fungal growth or morphogenesis changes, involving pathways like calcineurin/HSP90.[77]

Following Hurricane Katrina in 2005 (see **Table 1**), areas around New Orleans experienced a notable rise in respiratory issues, eye irritation, and asthma cases due to heightened exposure to mold and other airborne allergens.[78,79] Similarly, Hurricane Sandy's impact in 2012 along the Atlantic coast led to widespread flooding in states such as New York and New Jersey, where cleanup efforts exposed workers and residents to mold spores, doubling the likelihood of lower respiratory symptoms.[80] Inhalation of fungal spores can result in respiratory fungal infections, including conditions like fungal asthma and severe infections, particularly in individuals with weakened immune systems, or other respiratory conditions.[8,81] After Hurricane Harvey in Houston in 2017, there was a significant increase in invasive mold infections post-hurricane (3.69 cases) compared to pre-hurricane levels (2.50 cases), representing a rate ratio of 1.48 (95% confidence interval, 1.10 – 2.00).[82]

Wildfires and volcanic eruptions alter soil pH and nutrient levels, creating new fungal habitats. Fires also release fungal spores into the air, potentially affecting distant populations.[9] Exposure to wildfire smoke in California was found to significantly increase hospital admissions for coccidioidomycosis by 20% in the month following exposure, according to a retrospective study using the hospital administrative data from 22 hospitals.[57] These findings underscore the need for further research into the health impacts of wildfire smoke, particularly its role in transporting microbes that can lead to systemic fungal infections.[57]

Efforts to mitigate health risks post-disaster include intensive cleaning, ventilation improvement, and education on maintaining healthy indoor environments. For larger mold infestations, it is recommended to enlist skilled workers from specialized companies. Personnel involved in remediation should wear protective gear like gloves, glasses, and masks, and utilize strong biocides such as chlorine bleach. Long-term remediation strategies should combine physical methods such as thorough cleaning, repairing leaks, and implementing adequate ventilation and heating systems (eg, air purifiers and mechanical ventilation). Education-based approaches are also crucial to promote behaviors that maintain healthy home environments.[9,83]

DISCUSSION

The Earth's climate has undergone natural variations over the past 650,000 years, driven primarily by subtle changes in its orbit affecting solar energy received. However, the current warming trend is largely unprecedented in the last 1300 years and is primarily attributed to human activities, as affirmed by 97% of climate scientists. This consensus is supported by multiple lines of evidence, including the heat-trapping properties of greenhouse gases like carbon dioxide, which have been known since the 19th century.

Key indicators of climate change include rising global temperatures, evidenced by surface temperature reconstructions showing consistent warming since 1880, with the last few decades experiencing the most significant increases. The oceans have absorbed much of this heat, leading to warming sea temperatures and contributing to the decline in Arctic Sea ice and glacial retreat worldwide. Extreme weather events, such as record-high temperatures and intense rainfall, are becoming more frequent, while ocean acidification is accelerating due to increased carbon dioxide emissions.[71,84]

Climate change has profoundly impacted the framework of human fungal diseases resulting in multifaceted pathophysiological interrelations between various phenomena including direct effects on fungi, as well as the human host. Due to their complexity, underlying mechanisms are and need to be studied individually, yet presenting an interdependent network, which simultaneously evolves. Further developments are hard to foresee and may be unprecedented. Seemingly minor events may cumulate in highly impactful consequences for human health and safety.

With fungi adapting to rising temperatures, first potential consequences in terms of novel pathogenic species can currently be acknowledged. This observed adaption of fungal pathogens is paralleled by increasing virulence though various mechanisms like greater resistance to oxidative stress, pH changes, UV radiation, and antifungal drugs. Increasing frequencies of extreme weather events, rising temperatures and ongoing globalization allow fungal pathogens to spread influencing local ecosystems increasing exposure to fungi. Fungi that were once limited to specific regions are now becoming significant infectious etiologic agents in areas that previously had little exposure to such infections, which may come along with shortcomings in diagnosis of diseases and management. Detrimental effects on agricultural productivity have led to a

growing reliance on fungicides to protect crops, which in turn may accelerate the development of antifungal resistance in pathogens, posing an endangering circumstance for both food security and public health. Future consequences for antifungal therapy are hard to predict and meticulous monitoring of resistance dynamics especially once novel agents like olorofim enter the stage of broad clinical usage is warranted.

These impacts on the fungus itself are encompassed by consequences on the human host itself, which may even extend the opportunities of fungal-human influence. Human immunity and hence susceptibility to fungal diseases is compromised in many ways examined earlier. Above all, social determinants of health and host susceptibility is closely related, unproportionally affecting the global poor (see **Fig. 2**). Fungal outbreaks can be particularly devastating in areas with limited medical infrastructure and inadequate capabilities for diagnosing or treating such infections. Particularly in those areas under-reporting of fungal outbreaks due to health care constraints and diagnostic challenges remains common, emphasizing the need for continuous monitoring and targeted remediation strategies.

Addressing the effects of climate change on fungal ecosystems and the rising incidence of invasive fungal diseases presents a complex global challenge. High-income countries with greater resources available and advanced health care infrastructures have a responsibility to significantly invest in efforts to tackle these challenges. Fungal diseases are increasingly global in scope, affecting almost every part of planet Earth in different manners. Hence, collaboration is a key to addressing this global health challenge. Countries and regions can learn from each other's experiences and share best practices for managing fungal diseases in a changing climate.

Notoriously demonstrated by *C. auris* every novel fungal pathogen might come along with a unique set of challenges. Hence, resources must be allocated to research, innovation, surveillance, and public awareness campaigns. Especially in low- and middle-income countries, where health care systems are under strain, investment in health care infrastructure, access to antifungal medications, and training for health care professionals is vital. These efforts might be the best available preparation for future fungal disease related events.

SUMMARY

The impact of climate change on fungal pathogens and diseases is an urgent global issue that affects countries across all income levels, yet potentially unevenly affecting the global poor. Collaborative multifaceted global efforts are needed to mitigate the harmful effects of climate change and to deepen our understanding of the links between climate changes, attributes of fungal pathogens, and impact on human hosts. These efforts are crucial for improving prevention, detection, and treatment strategies.

CLINICS CARE POINTS

- *Pearls:*
  - *Early Diagnosis and Surveillance*: Implement comprehensive diagnostic testing for fungal infections, particularly in areas experiencing climate-driven changes in disease patterns and emergence of new pathogens. Early identification can improve treatment outcomes and reduce disease spread.
  - *Infection Control Practices:* Adhere to strict infection control measures, including protective equipment and proper sanitation, especially in environments affected by natural disasters and settings that previously experienced *C. auris* outbreaks. This can mitigate fungal exposure and infection risks.

- *Antifungal Stewardship in Clinics and Environment:* Use antifungal medications cautiously to minimize resistance development. Employ stewardship programs to monitor and optimize antifungal use in clinical settings but also create appropriate measures to regulate fungicide use in agriculture, reducing the risk of cross-resistance.
- *Public Health Collaboration*: Engaging in public health initiatives to enhance surveillance and response strategies for fungal diseases around the world is a key. Climate change exacerbates inequalities and social determinants of health resulting in disproportionate impact on fungal diseases. Collaboration with global health organizations can improve understanding and management of emerging fungal threats.
- *Targeted Remediation and Antifungal Therapy:* Remediation is a key in the aftermath of natural disasters that come with flooding events. Utilize susceptibility testing to guide antifungal therapy and combat resistance. Customized treatment plans are crucial, especially in areas with high antifungal resistance.

- *Pitfalls:*
  - *Delayed Diagnosis*: Avoid delays in diagnosing fungal infections due to atypical presentations or lack of awareness about climate-related shifts in disease patterns. Late diagnosis can lead to severe outcomes and increased mortality.
  - *Overlooked Emerging Fungal Threats:* Failing to account for emerging fungal pathogens that adapt to new environmental conditions can lead to underdiagnosis and mismanagement.
  - *Over-Reliance on Empiric Broad-Spectrum Antifungals*: Relying too heavily on empiric broad-spectrum antifungals without identification of the causative pathogen delays the identification of emerging fungal pathogens.
  - *Neglecting the Risk of Fungal Outbreaks in the Context of Natural Disasters:* Underestimating the risk of fungal outbreaks in the contest of natural disasters results in lack of diagnoses and inadequate management of such outbreaks.
  - *Inadequate Remediation Post-disasters:* Failing to implement comprehensive remediation strategies following natural disasters can exacerbate fungal outbreaks. Ensure thorough cleaning, drying, and repair of affected areas to prevent mold growth.

DISCLOSURE

S. Sedik and M. Egger declare no conflict of interest. M. Hoenigl received research funding and honoraria from Gilead, Astellas, MSD, IMMY, Pulmocide, Shionogi, Melinta, Mundipharma, Scynexis, F2G, and Pfizer - outside of the submitted work.

REFERENCES

1. Rocha J, Oliveira S, Viana CM, et al. Chapter 8 - climate change and its impacts on health, environment and economy. In: Prata JC, Ribeiro AI, Rocha-Santos T, editors. One health. Academic Press; 2022. p. 253–79.
2. Warmer climate may drive fungi to be more dangerous to our health. Available at: https://www.sciencedaily.com/releases/2023/01/230131160543.htm. Accessed July 8, 2024.
3. Caminade C, McIntyre KM, Jones AE. Impact of recent and future climate change on vector-borne diseases. Ann N Y Acad Sci 2019;1436(1):157–73.
4. Heatwaves, spread of infectious diseases due to climate change growing health threats to Europeans. Available at: https://www.eea.europa.eu/en/newsroom/news/heatwaves-spread-infectious-diseases. Accessed July 8, 2024.
5. Neabore LK. Wake-up call: rapid increase in human fungal diseases under climate change. Environmental Health Perspectives 2024;132(4):042001.
6. Nnadi NE, Carter DA. Climate change and the emergence of fungal pathogens. PLoS Pathog 2021;17(4):e1009503.

7. Hoenigl M. When disaster strikes fungi take control. Lancet Respir Med 2022; 10(12):1104–6.
8. Benedict K, Park BJ. Invasive fungal infections after natural disasters. Emerg Infect Dis 2014;20(3):349–55.
9. Seidel D, Wurster S, Jenks JD, et al. Impact of climate change and natural disasters on fungal infections. Lancet Microbe 2024. https://doi.org/10.1016/S2666-5247(24)00039-9.
10. Climate and Fungal Diseases. CDC U.S. Centers for disease control and prevention. Available at: https://www.cdc.gov/fungal/about/climate-change-and-fungal-diseases.html#:~:text=With%20shifting%20temperatures2C%20fungi%20may,of%20fungi%20to%20infect%20people. Accessed June 17, 2024.
11. Fanfair RN, Benedict K, Bos J, et al. Necrotizing cutaneous mucormycosis after a tornado in Joplin, Missouri, in 2011. N Engl J Med 2012;367(23):2214–25.
12. Andresen D, Donaldson A, Choo L, et al. Multifocal cutaneous mucormycosis complicating polymicrobial wound infections in a tsunami survivor from Sri Lanka. Lancet 2005;365(9462):876–8.
13. Snell BJ, Tavakoli K. Necrotizing fasciitis caused by Apophysomyces elegans complicating soft-tissue and pelvic injuries in a tsunami survivor from Thailand. Plast Reconstr Surg 2007;119(1):448–9.
14. Climate change could make fungi more dangerous, Available at: https://www.science.org/content/article/climate-change-could-make-fungi-more-dangerous (Accessed 4 July 2024).
15. Williams SL, Toda M, Chiller T, et al. Effects of climate change on fungal infections. PLoS Pathog 2024;20(5):e1012219.
16. Money NP. Fungal thermotolerance revisited and why climate change is unlikely to be supercharging pathogenic fungi (yet). Fungal Biol 2024;128(1):1638–41.
17. Huang J, Hu P, Ye L, et al. Pan-drug resistance and hypervirulence in a human fungal pathogen are enabled by mutagenesis induced by mammalian body temperature. Nat Microbiol 2024;9(7):1686–99.
18. Mattoon ER, Casadevall A, Cordero RJB. Beat the heat: correlates, compounds, and mechanisms involved in fungal thermotolerance. Fungal Biol Rev 2021;36:60–75.
19. Fernandes KE, Dwyer C, Campbell LT, et al. Species in the Cryptococcus gattii complex differ in capsule and cell size following growth under capsule-inducing conditions. mSphere 2016;1(6). https://doi.org/10.1128/mSphere.00350-16.
20. Kidd SE, Chow Y, Mak S, et al. Characterization of environmental sources of the human and animal pathogen Cryptococcus gattii in British Columbia, Canada, and the Pacific Northwest of the United States. Appl Environ Microbiol 2007;73(5):1433–43.
21. Casadevall A, Kontoyiannis DP, Robert V. On the emergence of Candida auris: climate change, azoles, swamps, and birds. mBio 2019;10(4). https://doi.org/10.1128/mBio.01397-19.
22. Casadevall A, Kontoyiannis DP, Robert V. Environmental Candida auris and the global warming emergence hypothesis. mBio 2021;12(2). https://doi.org/10.1128/mBio.00360-21.
23. del Olmo V, Mixão V, Fotedar R, et al. Origin of fungal hybrids with pathogenic potential from warm seawater environments. Nat Commun 2023;14(1):6919.
24. Arendrup MC, Arikan-Akdagli S, Jørgensen KM, et al. European candidaemia is characterised by notable differential epidemiology and susceptibility pattern: results from the ECMM Candida III study. J Infect 2023;87(5):428–37.

25. Xiao W, Zhang J, Huang J, et al. Response and regulatory mechanisms of heat resistance in pathogenic fungi. Appl Microbiol Biotechnol 2022;106(17):5415–31.
26. Avery SV, Singleton I, Magan N, et al. The fungal threat to global food security. Fungal Biol 2019;123(8):555–7.
27. Food Security: How do crop plants combat pathogens? Available at: https://www.ars.usda.gov/oc/dof/food-security-how-do-crop-plants-combat-pathogens (Accessed 4 July 2024).
28. Zubrod JP, Bundschuh M, Arts G, et al. Fungicides: an overlooked pesticide class? Environ Sci Technol 2019;53(7):3347–65.
29. Fisher MC, Henk DA, Briggs CJ, et al. Emerging fungal threats to animal, plant and ecosystem health. Nature 2012;484(7393):186–94.
30. Hoenigl M, Seidel D, Sprute R, et al. COVID-19-associated fungal infections. Nat Microbiol 2022;7(8):1127–40.
31. Hoenigl M, Arastehfar A, Arendrup MC, et al. Novel antifungals and treatment approaches to tackle resistance and improve outcomes of invasive fungal disease. Clin Microbiol Rev 2024;37(2):e00074–123.
32. Gow NAR, Johnson C, Berman J, et al. The importance of antimicrobial resistance in medical mycology. Nat Commun 2022;13(1):5352.
33. Lucas JA, Hawkins NJ, Fraaije BA. Chapter two - the evolution of fungicide resistance. In: Sariaslani S, Gadd GM, editors. Advances in applied microbiology. Academic Press; 2015. p. 29–92.
34. Verweij PE, Lucas JA, Arendrup MC, et al. The one health problem of azole resistance in Aspergillus fumigatus: current insights and future research agenda. Fungal Biol Rev 2020;34(4):202–14.
35. Cao D, Wang F, Yu S, et al. Prevalence of azole-resistant Aspergillus fumigatus is highly associated with azole fungicide residues in the fields. Environ Sci Technol 2021;55(5):3041–9.
36. Celia-Sanchez BN, Mangum B, Gómez Londoño LF, et al. Pan-azole- and multi-fungicide-resistant Aspergillus fumigatus is widespread in the United States. Appl Environ Microbiol 2024;90(4):e0178223.
37. Arastehfar A, Carvalho A, Houbraken J, et al. Aspergillus fumigatus and aspergillosis: from basics to clinics. Stud Mycol 2021;100:100115.
38. Berger S, El Chazli Y, Babu AF, et al. Azole resistance in Aspergillus fumigatus: a consequence of antifungal use in agriculture? Mini review. Front Microbiol 2017;8. https://doi.org/10.3389/fmicb.2017.01024.
39. Bastos RW, Rossato L, Goldman GH, et al. Fungicide effects on human fungal pathogens: cross-resistance to medical drugs and beyond. PLoS Pathog 2021;17(12):e1010073.
40. Verweij PE, Snelders E, Kema GHJ, et al. Azole resistance in Aspergillus fumigatus: a side-effect of environmental fungicide use? Lancet Infect Dis 2009;9(12):789–95.
41. Hagiwara D. Isolation of azole-resistant Aspergillus fumigatus from imported plant bulbs in Japan and the effect of fungicide treatment. J Pestic Sci 2020;45(3):147–50.
42. Chowdhary A, Sharma C, Meis JF. Candida auris: a rapidly emerging cause of hospital-acquired multidrug-resistant fungal infections globally. PLoS Pathog 2017;13(5):e1006290.
43. Hoenigl M, Jenks JD, Egger M, et al. Treatment of Fusarium infection of the central nervous system: a review of past cases to guide therapy for the ongoing

2023 outbreak in the United States and Mexico. Mycopathologia 2023;188(6):973–81.
44. Hoenigl M, Salmanton-García J, Walsh TJ, et al. Global guideline for the diagnosis and management of rare mould infections: an initiative of the European confederation of medical mycology in cooperation with the international society for human and animal mycology and the American society for microbiology. Lancet Infect Dis 2021;21(8):e246–57.
45. Lestrade PP, Bentvelsen RG, Schauwvlieghe AFAD, et al. Voriconazole resistance and mortality in invasive aspergillosis: a multicenter retrospective cohort study. Clin Infect Dis 2018;68(9):1463–71.
46. Rhijn N, Storer I, Birch M, et al. The novel agrochemical fungicide ipflufenoquin drives cross-resistance to olorofim in the human pathogen Aspergillus fumigatus. Res Sq 2023.
47. Vazquez Jose A, Pappas PG, Boffard K, et al. Clinical efficacy and safety of a novel antifungal, fosmanogepix, in patients with candidemia caused by Candida auris: results from a phase 2 trial. Antimicrob Agents Chemother 2023;67(5):e01419–22.
48. McLellan CA, Whitesell L, King OD, et al. Inhibiting GPI anchor biosynthesis in fungi stresses the endoplasmic reticulum and enhances immunogenicity. ACS Chem Biol 2012;7(9):1520–8.
49. Hatamoto M, Aizawa R, Koda K, et al. Aminopyrifen, a novel 2-aminonicotinate fungicide with a unique effect and broad-spectrum activity against plant pathogenic fungi. J Pestic Sci 2021;46(2):198–205.
50. Soliciting feedback on a proposed regulatory framework to assess the risk to the effectiveness of human and animal drugs posed by certain antibacterial or antifungal pesticides. Available at: https://www.regulations.gov/docket/EPA-HQ-OPP-2023-0445 (Accessed 7 July 2024).
51. Valley Fever (Coccidioidomycosis). Facts and stats about Valley fever. Available at: https://www.cdc.gov/valley-fever/php/statistics/index.html. Accessed July 8, 2024.
52. Gorris ME, Treseder KK, Zender CS, et al. Expansion of coccidioidomycosis endemic regions in the United States in response to climate change. Geohealth 2019;3(10):308–27.
53. Antinori S, Giacomelli A, Corbellino M, et al. Histoplasmosis diagnosed in Europe and Israel: a case report and systematic review of the literature from 2005 to 2020. J Fungi 2021;7(6):481.
54. Chen L, Hu D, Zhang C, et al. Histoplasmosis: an epidemiological and clinical update in China, review and a case report. Mycology 2024;15(1):101–9.
55. Wilmes D, Mayer U, Wohlsein P, et al. Animal histoplasmosis in Europe: review of the literature and molecular typing of the etiological agents. J Fungi (Basel) 2022;8(8). https://doi.org/10.3390/jof8080833.
56. How climate change could make fungal diseases worse. Knowable magazine. Available at: https://www.gavi.org/vaccineswork/how-climate-change-could-make-fungal-diseases-worse?gad_source=1&gclid=CjwKCAjwyJqzBhBaEiwAWDRJVKmmDwo2Ne7jYq_wOC3wB5snjkyiL2U_ONSdCukKZkUX4SPoGCnbHBoCqWsQAvD_BwE. Accessed June 10, 2024.
57. Mulliken JS, Hampshire KN, Rappold AG, et al. Risk of systemic fungal infections after exposure to wildfires: a population-based, retrospective study in California. Lancet Planet Health 2023;7(5):e381–6.

58. Rieux A, Soubeyrand S, Bonnot F, et al. Long-distance wind-dispersal of spores in a fungal plant pathogen: estimation of anisotropic dispersal kernels from an extensive field experiment. PLoS One 2014;9(8):e103225.
59. Martinez-Bracero M, Markey E, Clancy JH, et al. Airborne fungal spore review, new advances and automatisation. Atmosphere 2022;13(2):308.
60. The national academies collection: reports funded by national institutes of health. In: Knobler S, Mahmoud A, Lemon S, et al, editors. The impact of globalization on infectious disease emergence and control: exploring the consequences and opportunities: workshop summary. (US): National Academies Press; 2006. Copyright © 2006, National Academy of Sciences.
61. Fisher MC, Gurr SJ, Cuomo CA, et al. Threats posed by the fungal kingdom to humans, wildlife, and agriculture. mBio 2020;11(3). https://doi.org/10.1128/mBio.00449-20.
62. Norval M, Halliday GM. The consequences of UV-induced immunosuppression for human health. Photochem Photobiol 2011;87(5):965–77.
63. Protsiv M, Ley C, Lankester J, et al. Decreasing human body temperature in the United States since the industrial revolution. Elife 2020;9. https://doi.org/10.7554/eLife.49555.
64. Chow NA, Gade L, Tsay SV, et al. Multiple introductions and subsequent transmission of multidrug-resistant Candida auris in the USA: a molecular epidemiological survey. Lancet Infect Dis 2018;18(12):1377–84.
65. McMichael C, Barnett J, McMichael AJ. An ill wind? Climate change, migration, and health. Environ Health Perspect 2012;120(5):646–54.
66. Daynes L. The health impacts of the refugee crisis: a medical charity perspective. Clin Med (Lond) 2016;16(5):437–40.
67. Dowell SF. Seasonal variation in host susceptibility and cycles of certain infectious diseases. Emerg Infect Dis 2001;7(3):369–74.
68. McLean MA, Angilletta MJ, Williams KS. If you can't stand the heat, stay out of the city: thermal reaction norms of chitinolytic fungi in an urban heat island. J Therm Biol 2005;30(5):384–91.
69. Jenks JD, Aneke CI, Al-Obaidi MM, et al. Race and ethnicity: risk factors for fungal infections? PLoS Pathog 2023;19(1):e1011025.
70. Egger M, Hoenigl M, Thompson GR 3rd, et al. Let's talk about sex characteristics - as a risk factor for invasive fungal diseases. Mycoses 2022. https://doi.org/10.1111/myc.13449.
71. Jenks JD, Prattes J, Wurster S, et al. Social determinants of health as drivers of fungal disease. eClinicalMedicine 2023;66:102325.
72. Salmanton-García J, Au WY, Hoenigl M, et al. The current state of laboratory mycology in asia/pacific: a survey from the European confederation of medical mycology (ECMM) and international society for human and animal mycology (ISHAM). Int J Antimicrob Agents 2023;106718. https://doi.org/10.1016/j.ijantimicag.2023.106718.
73. Driemeyer C, Falci DR, Oladele RO, et al. The current state of clinical mycology in Africa: a European confederation of medical mycology and international society for human and animal mycology survey. Lancet Microbe 2022;3(6):e464–70.
74. Larson N. Climate change spurs doubling of disasters since 2000: UN. Available at: https://phys.org/news/2020-10-climate-spurs-disasters.html. Accessed June 25, 2024.
75. Watson JT, Gayer M, Connolly MA. Epidemics after natural disasters. Emerg Infect Dis 2007;13(1):1–5. https://doi.org/10.3201/eid1301.060779.

76. Talley SM, Coley PD, Kursar TA. The effects of weather on fungal abundance and richness among 25 communities in the Intermountain West. BMC Ecol 2002;2:7.
77. Wurster S, Tatara AM, Albert ND, et al. Tornadic shear stress induces a transient, calcineurin-dependent hypervirulent phenotype in Mucorales molds. mBio 2020;11(3). https://doi.org/10.1128/mBio.01414-20.
78. Rath B, Young EA, Harris A, et al. Adverse respiratory symptoms and environmental exposures among children and adolescents following Hurricane Katrina. Public Health Rep 2011;126(6):853–60.
79. Rando RJ, Lefante JJ, Freyder LM, et al. Respiratory health effects associated with restoration work in post-Hurricane Katrina New Orleans. J Environ Public Health 2012;2012:462478.
80. Gargano LM, Locke S, Jordan HT, et al. Lower respiratory symptoms associated with environmental and reconstruction exposures after hurricane Sandy. Disaster Med Public Health Prep 2018;12(6):697–702.
81. Van Dyke MV, Quintero Duque F. After the storm: damp, moldy homes. Climate central. Available at: https://www.climatecentral.org/climate-matters/after-the-storm-damp-moldy-homes-2023. Accessed June 21, 2024.
82. Toda M, Williams S, Jackson BR, et al. Invasive mold infections following hurricane harvey-Houston, Texas. Open Forum Infect Dis 2023;10(3):ofad093.
83. 6, prevention and remediation of damp indoor environments. 2004.
84. Climate change: HOW do we KNOW?. Available at: https://thegreenicon.blogspot.com/2014/08/climate-change-how-do-we-know.html. Accessed July 8, 2024.
85. Nelson R. Emergence of resistant Candida auris. Lancet Microbe 2023;4(6):e396.
86. Horton MV, Holt AM, Nett JE. Mechanisms of pathogenicity for the emerging fungus Candida auris. PLoS Pathog 2023;19(12):e1011843.
87. Heaney H, Laing J, Paterson L, et al. The environmental stress sensitivities of pathogenic Candida species, including Candida auris, and implications for their spread in the hospital setting. Med Mycol 2020;58(6):744–55.
88. Constante CC, Monteiro AA, Alves SH, et al. Different risk factors for candidemia occur for Candida species belonging to the C. parapsilosis complex. Med Mycol 2014;52(4):403–6.
89. Pretorius ZA, Boshoff WHP, Kema GHJ. First report of puccinia striiformis f. sp. tritici on wheat in South Africa. Plant Dis 1997;81(4):424.
90. Rocher F, Alouane T, Philippe G, et al. Fusarium graminearum infection strategy in wheat involves a highly conserved genetic program that controls the expression of a core effectome. Int J Mol Sci 2022;23(3):1914.
91. Harris LJ, Desjardins AE, Plattner RD, et al. Possible role of trichothecene mycotoxins in virulence of Fusarium graminearum on maize. Plant Dis 1999;83(10):954–60.
92. Robbins N, Caplan T, Cowen LE. Molecular evolution of antifungal drug resistance. Annu Rev Microbiol 2017;71(2017):753–75.
93. Fraczek MG, Bromley M, Bowyer P. An improved model of the Aspergillus fumigatus CYP51A protein. Antimicrob Agents Chemother 2011;55(5):2483–6.
94. Snelders E, Camps SM, Karawajczyk A, et al. Triazole fungicides can induce cross-resistance to medical triazoles in Aspergillus fumigatus. PLoS One 2012;7(3):e31801.

95. Cooke E. New fungal infection discovered in China. Available at: https://www.livescience.com/health/viruses-infections-disease/new-fungal-infection-discovered-in-china (Accessed 14 July 2024).
96. Mahindra AS. Never-seen-before fungi kills two in the UK; what is this deadly infection?. Available at: https://www.timesnownews.com/health/never-seen-before-fungi-kills-two-in-the-uk-what-is-this-deadly-infection-article-111834991 (Accessed 14 July 2024).
97. Ashraf N, Kubat RC, Poplin V, et al. Re-Drawing the maps for endemic mycoses. Mycopathologia 2020;185(5):843–65.
98. Phillips S, Jones I, Sondermyer-Cooksey G, et al. Association between wildfires and coccidioidomycosis incidence in California, 2000-2018: a synthetic control analysis. Environ Epidemiol 2023;7(4):e254.
99. Kamali MAPDDMGLSCTJFSJDVBLMA. Notes from the field: coccidioidomycosis outbreak among wildland firefighters — California, 2021. Available at: https://www.cdc.gov/mmwr/volumes/71/wr/mm7134a4.htm#:%E2%88%BC:text=Illness%20onset%20and%20work%20history,exposure%20and%20without%20respiratory%20protection (Accessed 15 July 2024).
100. Maegele M, Gregor S, Yuecel N, et al. One year ago not business as usual: wound management, infection and psychoemotional control during tertiary medical care following the 2004 Tsunami disaster in southeast Asia. Crit Care 2006;10(2):R50.