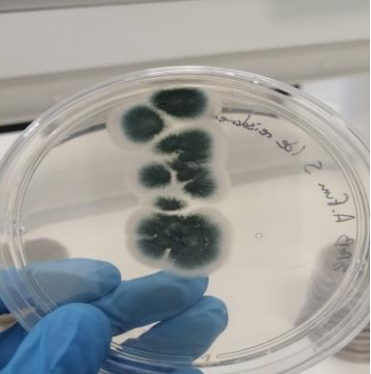
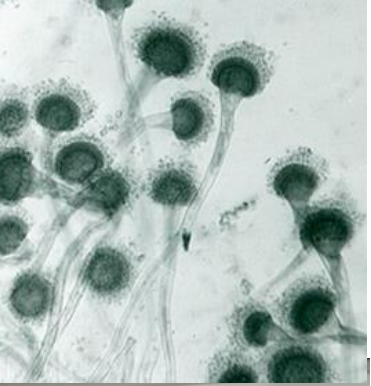


Climate change and the impact on fungi and mycotoxins

Carla Viegas* and Susana Viegas

carla.viegas@estesl.ipl.pt



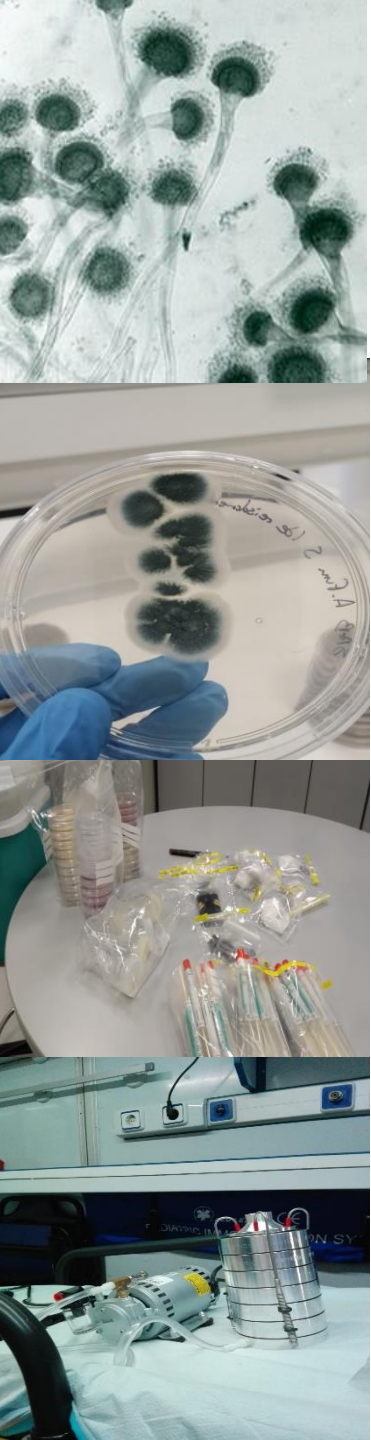
Outline

1 – Background

2 – Climate change: Impact on fungal diseases

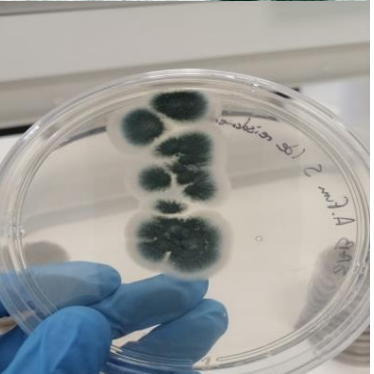
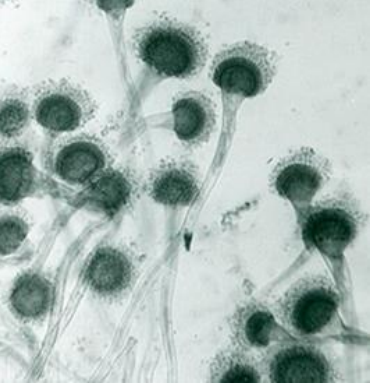
3 – Natural disasters and fungal outbreaks

4 – Main conclusions



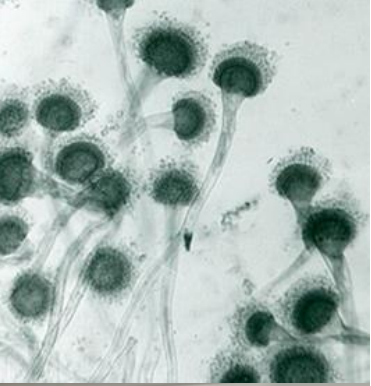
1 – Background

- The SDGs 3 and 8 highlight the need to guarantee healthy lives and encourage wellbeing and **decent work for all**.
- WHO recognized as **priority settings for action the workplaces** reporting more than 1.2 million deaths annually due to occupational risks.
- **Only a small fraction** of the general workforce has access to **occupational health surveillance**.



HERA from EU presented a priority list of **top-3 health threats that require coordination of measures at EU level**, since they have the potential of spreading across Member States:




















- **pathogens with high pandemic potential**
- **chemical, biological, radiological and nuclear threats**
- **threats resulting from antimicrobial resistance.**

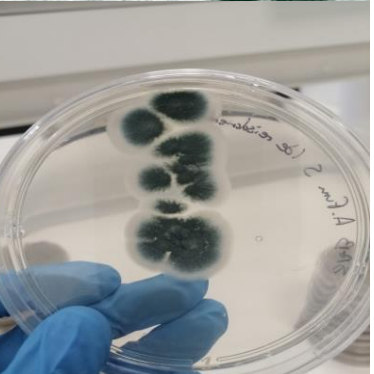
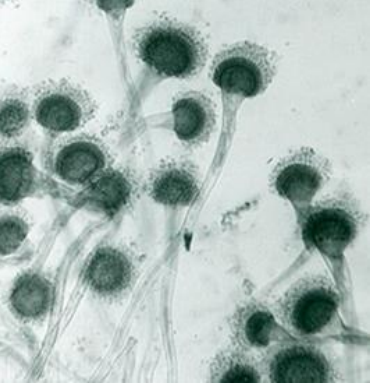


WHO release a list of fungal priority pathogens but without considering the toxicological relevance.

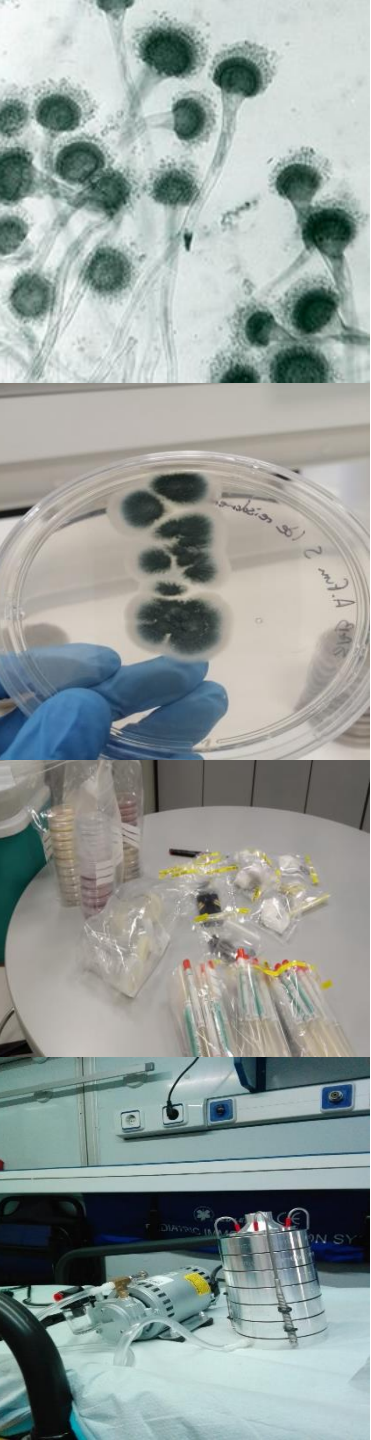


Table 3. WHO fungal priority pathogens list

Critical group	High group	Medium group
 <i>Cryptococcus neoformans</i>	 <i>Nakaseomyces glabrata</i> (<i>Candida glabrata</i>)	 <i>Scedosporium</i> spp.
 <i>Candida auris</i>	 <i>Histoplasma</i> spp.	 <i>Lomentospora prolificans</i>
 <i>Aspergillus fumigatus</i>	 Eumycetoma causative agents	 <i>Coccidioides</i> spp.
 <i>Candida albicans</i>	 Mucorales	 <i>Pichia kudriavzevii</i> (<i>Candida krusei</i>)
	 <i>Fusarium</i> spp.	 <i>Cryptococcus gattii</i>
	 <i>Candida tropicalis</i>	 <i>Talaromyces marneffeii</i>
	 <i>Candida parapsilosis</i>	 <i>Pneumocystis jirovecii</i>
		 <i>Paracoccidioides</i> spp.



- In all European countries employers are **obliged by regulation to assess and prevent exposure to occupational risks** (Directive 89/391/EEC) .
- The Directive 2000/54/EC of the European Parliament and the Council of September 18, 2000 **sets the rules regarding risk assessment if exposure to biological agents cannot be avoided (2000/54/EC, 2000).**



- Scientific evidence that associates occupational exposure to bioaerosols (bacteria, fungi and metabolites) to health outcomes.

(Kim et al. 2018; Sabino et al. 2019; Schlosser et al. 2020)



Medical Mycology, 2019, 57, S196–S205
doi: 10.1093/mmy/myy090
Review Article



Review Article

The role of occupational *Aspergillus* exposure in the development of diseases

Raquel Sabino^{1,2,*}, Cristina Verissimo¹, Carla Viegas^{3,4}, Susana Viegas^{3,4}, João Brandão⁵, Magna Alves-Correia⁶, Luís-Miguel Borrego^{6,7}, Karl V. Clemons^{8,9}, David A. Stevens^{8,9} and Malcolm Richardson^{10,11}

JOURNAL OF ENVIRONMENTAL SCIENCES 67 (2018) 23–35



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Airborne bioaerosols and their impact on human health

Ki-Hyun Kim^{1,*}, Ehsanul Kabir², Shamin Ara Jahan³

Waste Management 105 (2020) 395–404

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman



Airborne mycotoxins in waste recycling and recovery facilities: Occupational exposure and health risk assessment

Olivier Schlosser*, Samuel Robert, Naïke Noyon

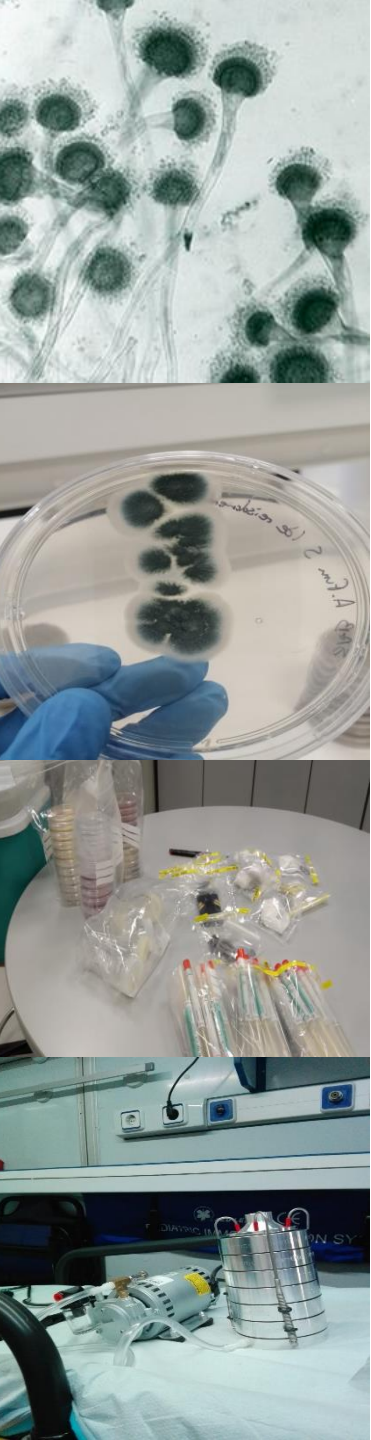
SUEZ, CIRSEE, 38 rue du Président Wilson, 78230 Le Pecq, France



Impact of climate change and natural disasters on fungal infections

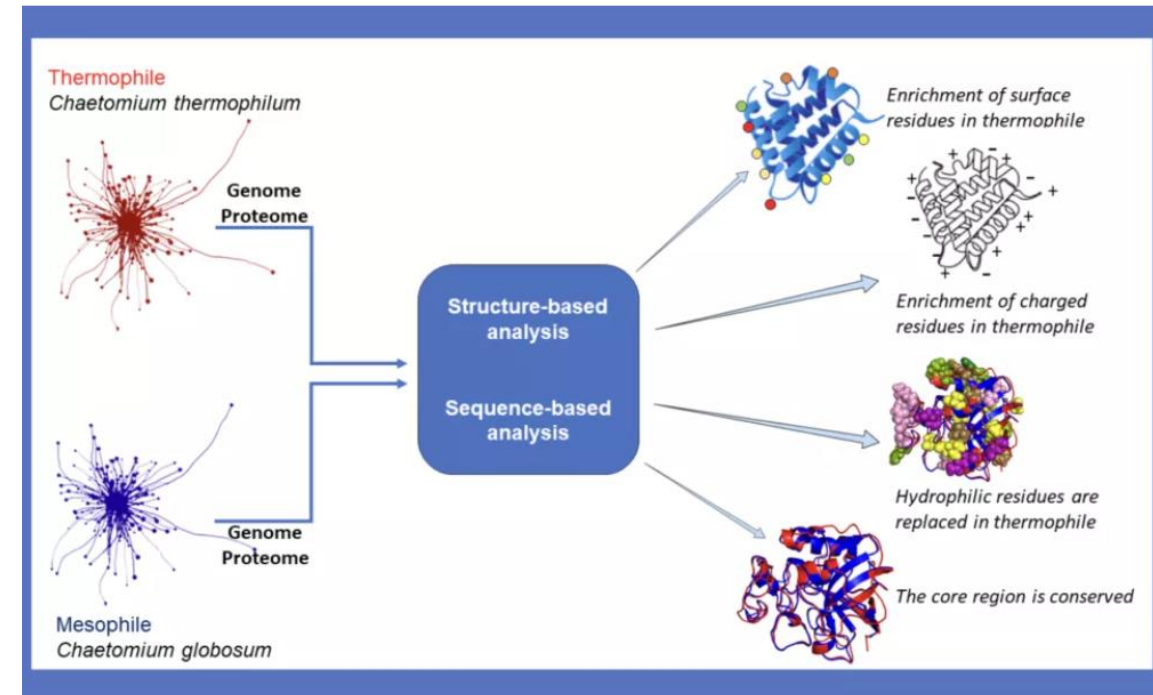
Daniela Seidel*, Sebastian Wurster*, Jeffrey D Jenks*, Hatim Sati, Jean-Pierre Gangneux, Matthias Egger, Ana Alastruey-Izquierdo, Nathan P Ford, Anuradha Chowdhary, Rosanne Sprute, Oliver Cornely, George R Thompson III, Martin Hoenigtl, Dimitrios P Kontoyiannis†

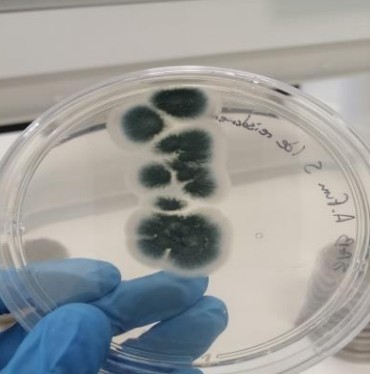
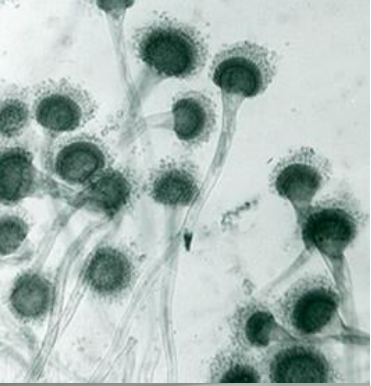




2 – Climate change: impact on fungal diseases

- Some pathogenic fungi are benefiting from climate change, gradually adapting to higher temperatures and becoming more prevalent and virulent.
- Certain proteins on the outside of fungi play a crucial role in making them heat-resistant.

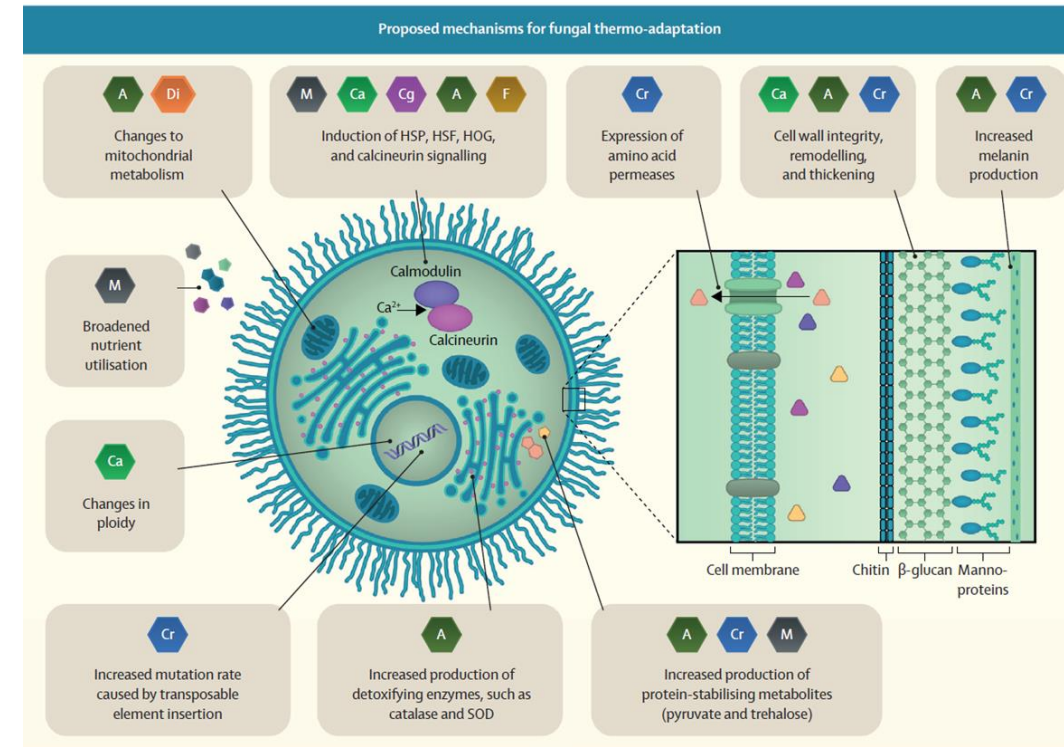




- Thermal adaptation is not the sole factor but represents a major prerequisite for infecting humans or mammals.
- Rising environmental temperatures might allow for the fungal stress adaptation machinery to adapt to high-temperature environments

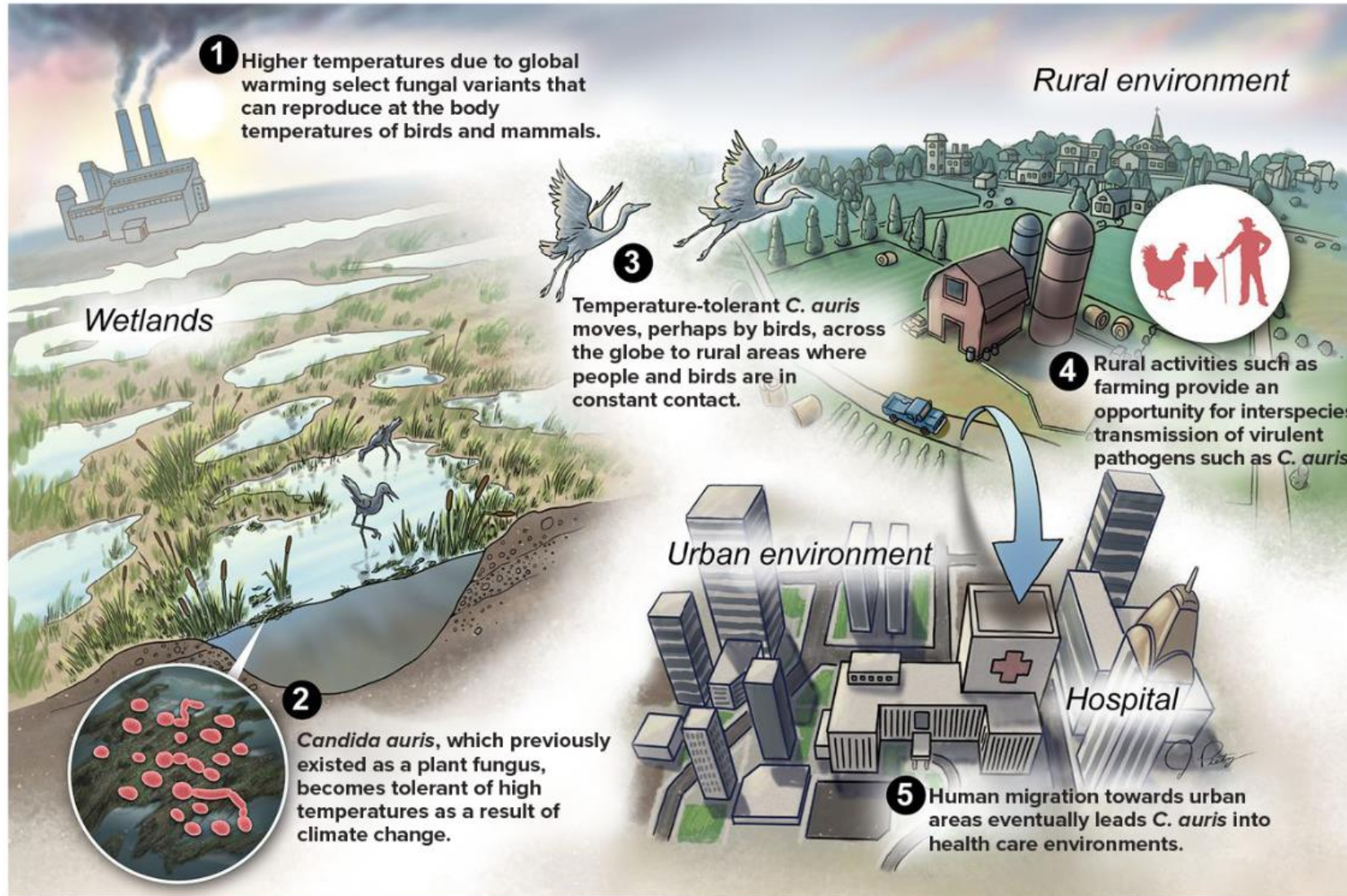


**Promoting their
pathogenicity in humans**



(Seidel et al. 2024)

How *Candida auris* may have spread to people



The drivers of climate change and

lost of (micro)biodiversity:

- Changes in the use of land and sea
- Intensive animal production
- Invasive species
- Pollution
- Exploitation of natural resources

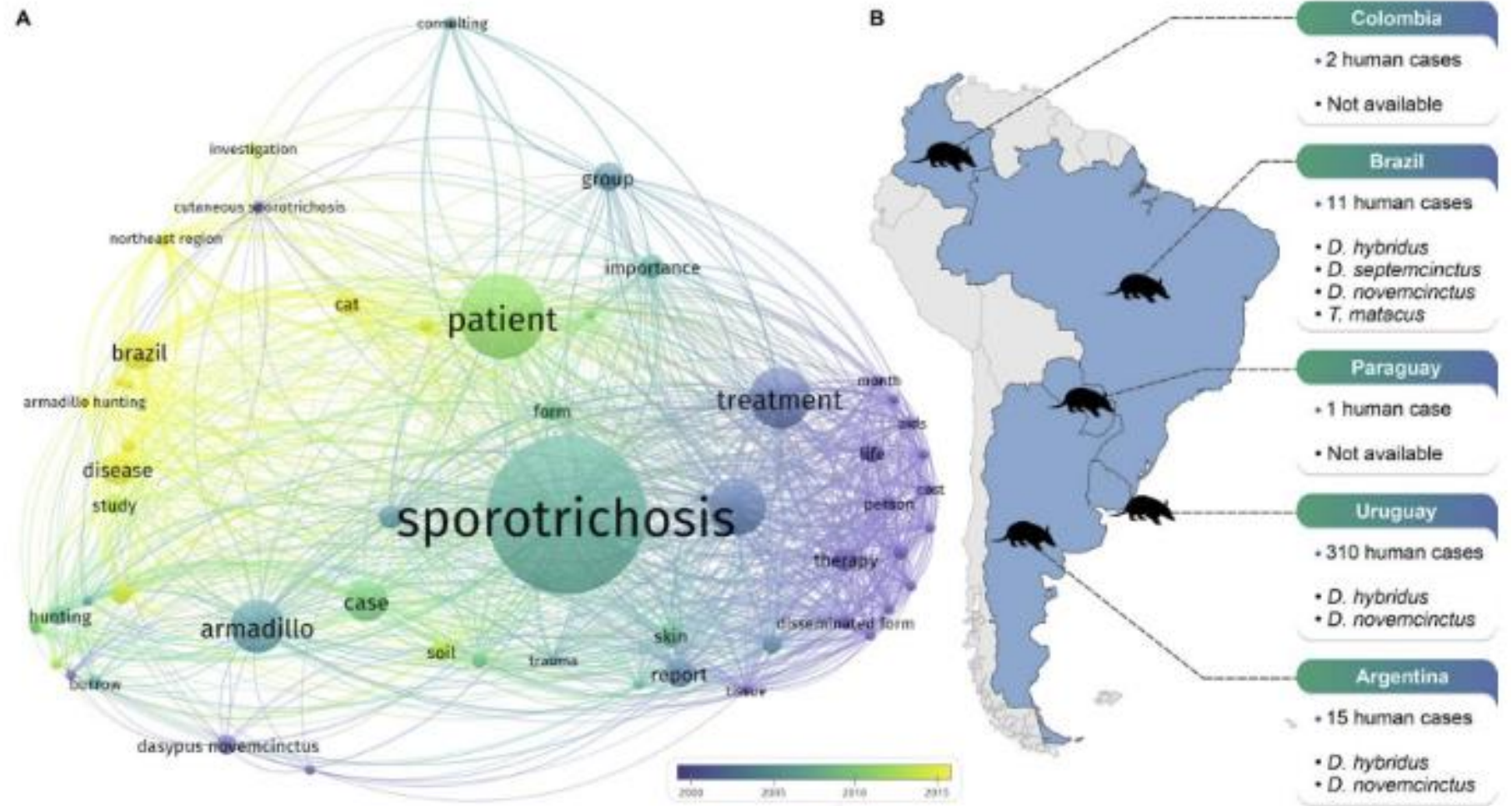
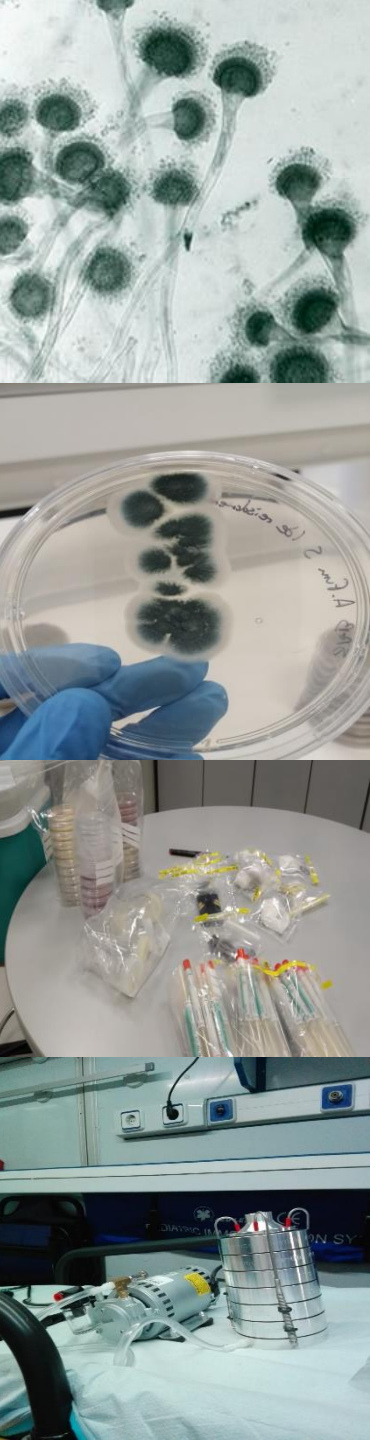


Climate changes



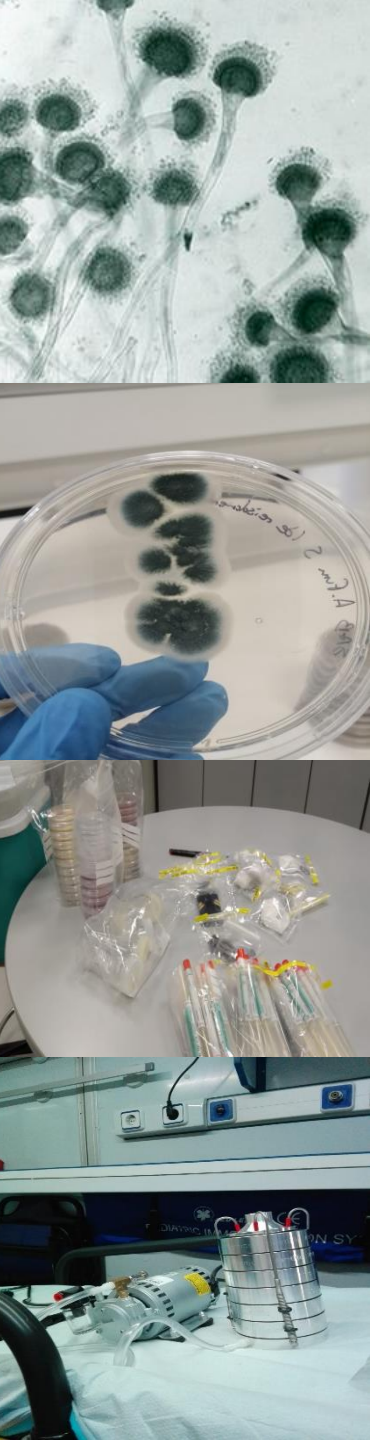
Shaping microbial diversity

Thermotolerant fungi



Multifocal Sporotrichosis Associated with Armadillo Hunting in Midwest Brazil

<https://lnkd.in/eiiPjTvY>



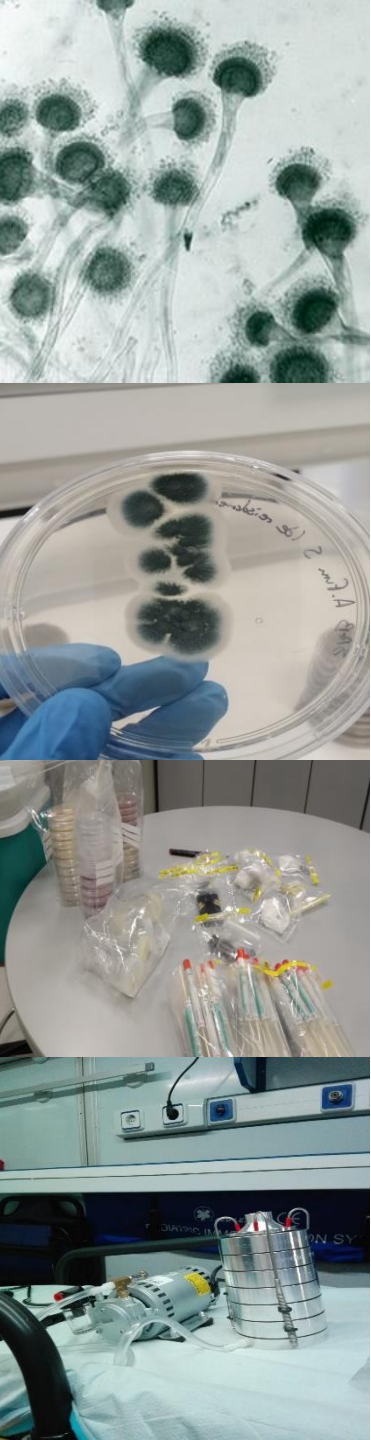
The adaptation of pathogenic fungi to one environmental stressor also primes them to overcome other adverse environments. This observation extends to several drivers associated with climate change.

Ex. 1: Fungal melanin confers cross-protection against:

- heat stress
- pH stress
- heavy metals
- and radioactive isotopes

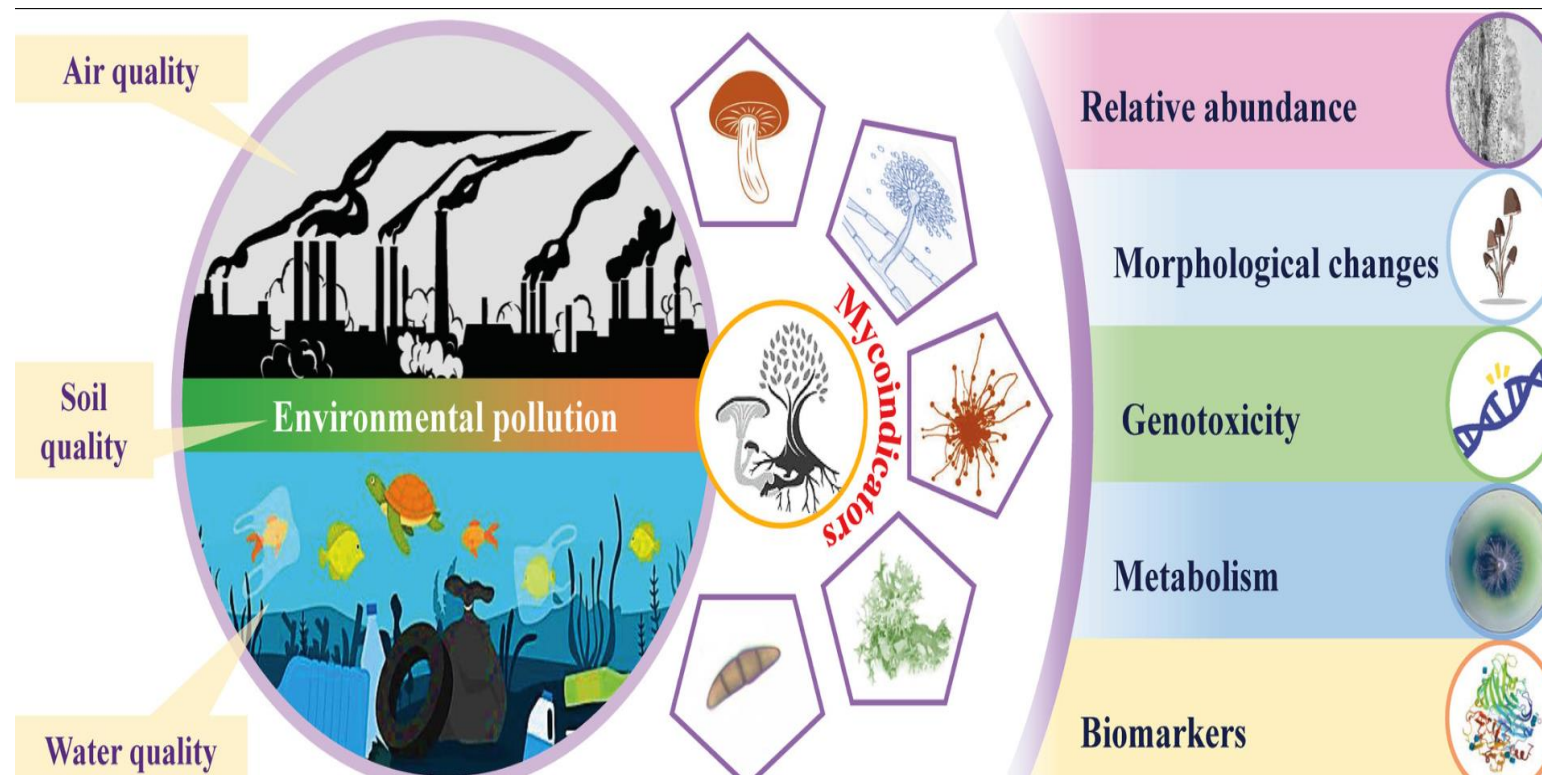


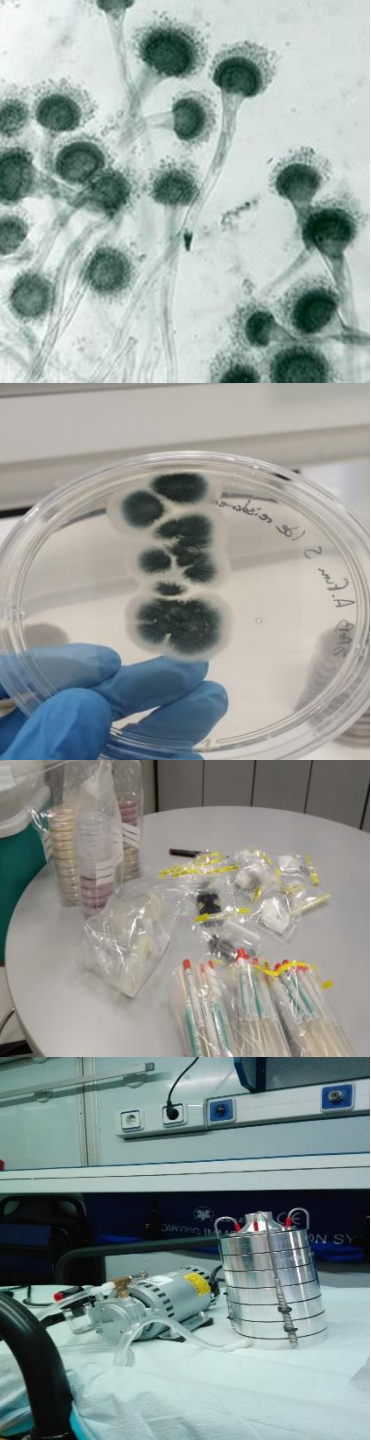
contributing to the ability of some fungal taxa to proliferate in metal-polluted areas, acidic environments, and radioactively polluted wastelands after nuclear catastrophes.



Ex. 2 - Pollution of water bodies and water supply systems has been associated with increased growth and diversity of fungi, including pathogenic species, as many pollutants can provide a favourable pH and nutritional environment for fungal growth.

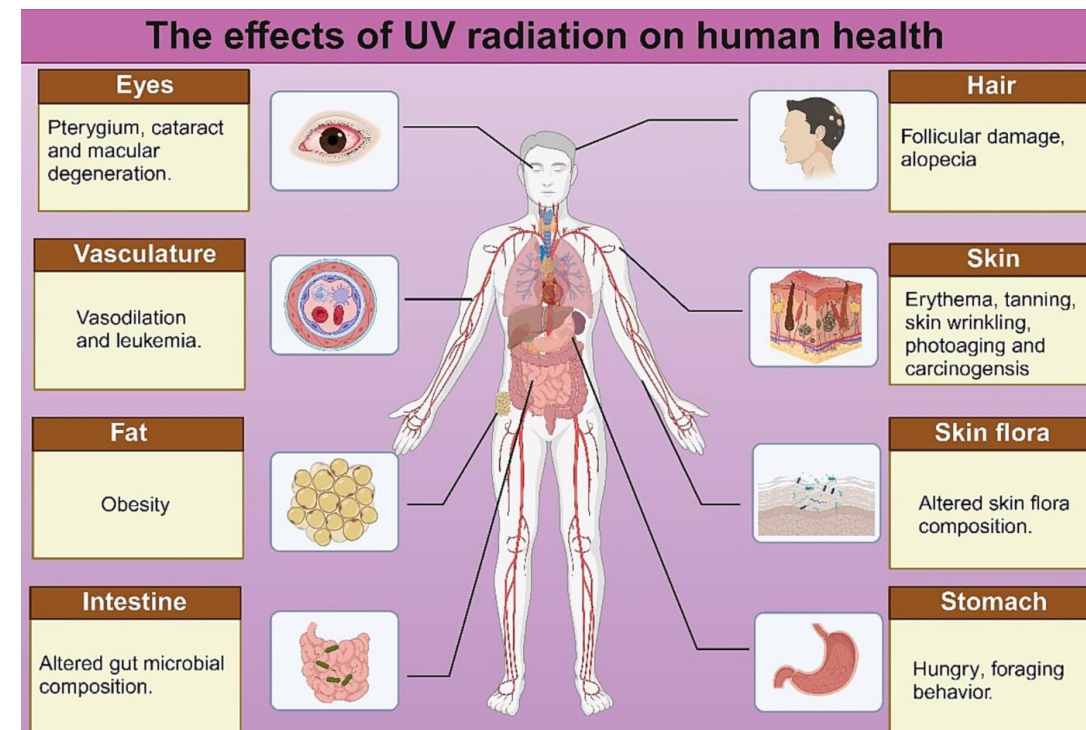
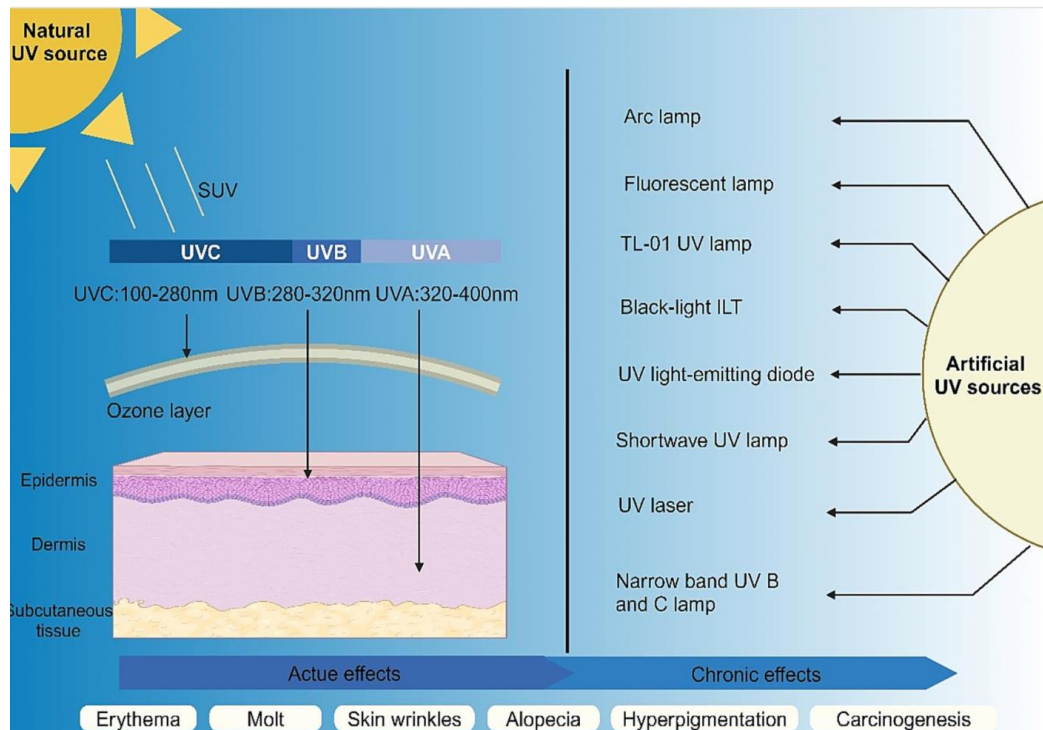
(Ortiz-Vera et al. 2018)

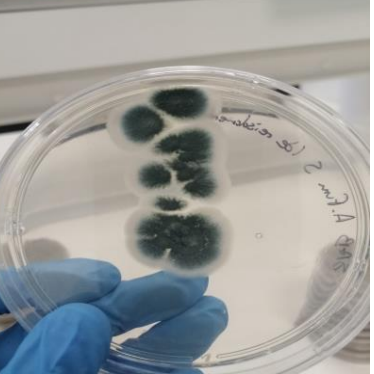
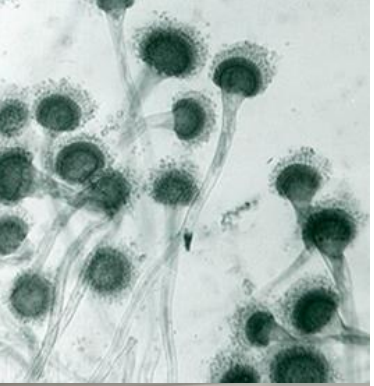




Ex. 3 - Increased ultraviolet light exposure has been linked to numerous adverse effects on human immunity and immune responses, including unfavourable T-cell polarisation, increased production of inhibitory cytokines, and altered complement activation.

(Norval and Halliday 2011)





Ex. 4: As environmental temperatures have been rising, the average human body temperatures have decreased due to improved standards of living.

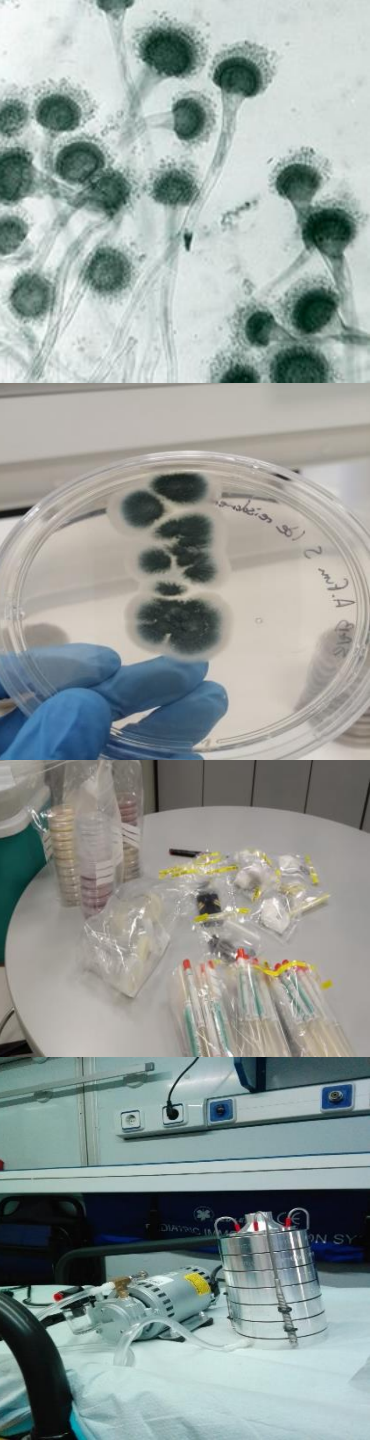
The narrowing of the thermal exclusion gradient between fungi and humans could further lead to alignment between host and fungal temperature preferences and **increase human susceptibility to environmental fungi.**



Warmer ambient temperatures may enable nonpathogenic fungi to acquire the ability to infect warm-blooded hosts.

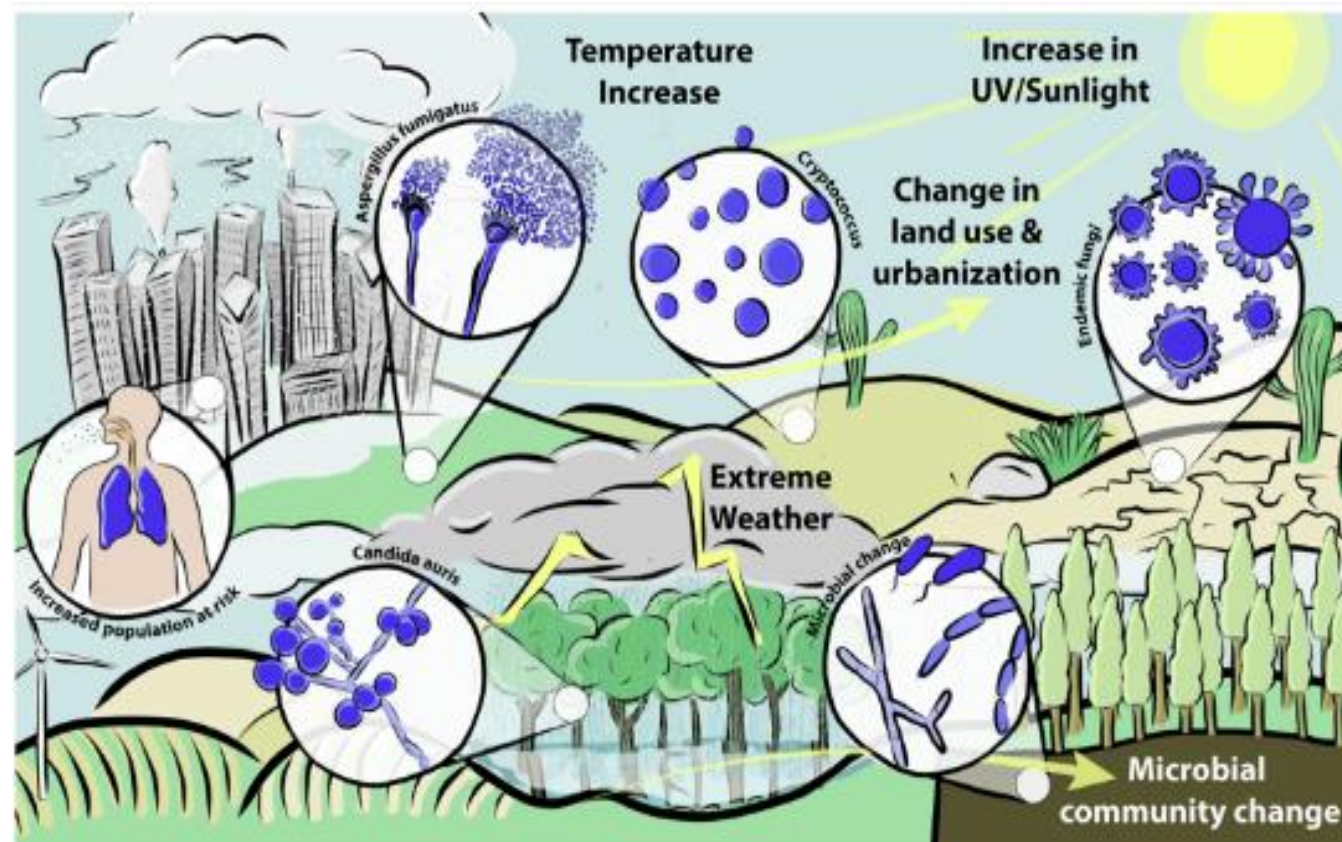
(Protsiv et al. 2020; Cohen et al. 2017)

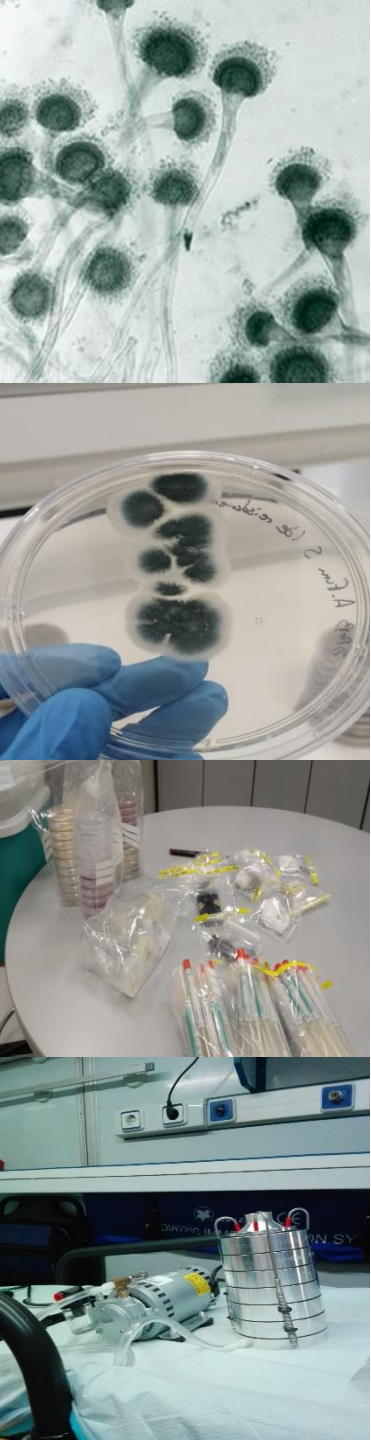




Ex. 5 - Seasonal influences on meteorological conditions and changes in warming patterns, along with alterations in light–dark cycles, melatonin secretion, and potential disruptions in circadian rhythms can also **affect host susceptibility**, including changes in the immune response, alterations in the expression of epithelial receptors, and changes in mucosal surface characteristics.

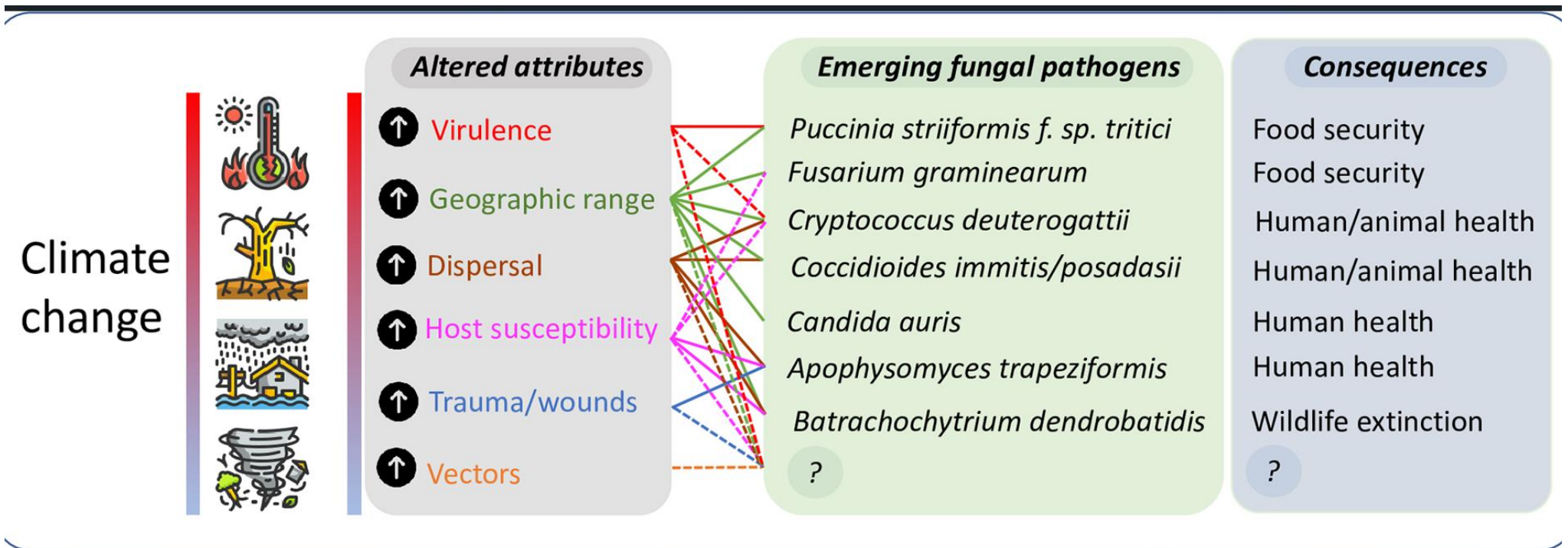
(Arastehfar et al. 2021; Carter et al. 2021; Dowell 2001)



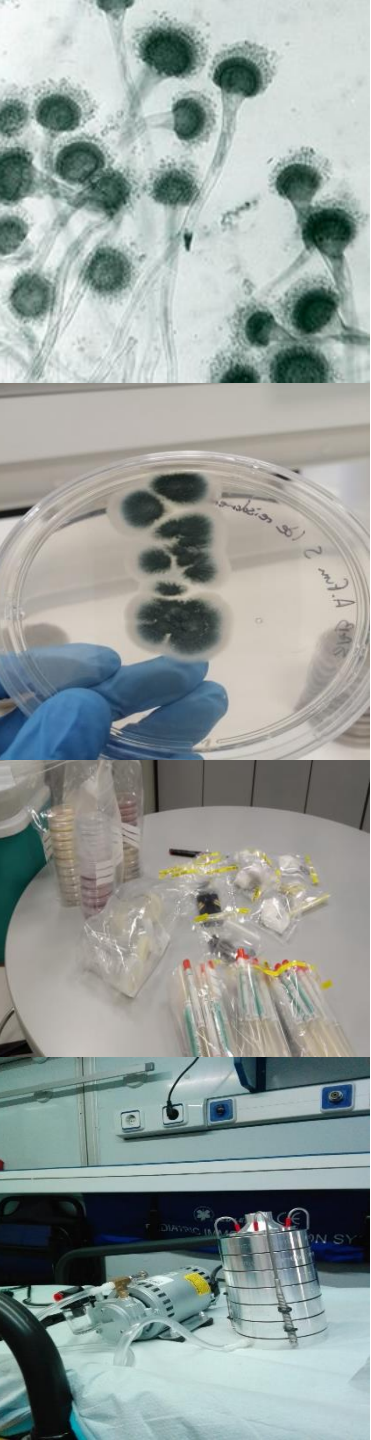


Ex. 6 – Fungal plant pathogens such as *Puccinia striiformis* or *Fusarium graminearum* are evolving with climate change and threatening food security. Food insecurity and nutrient deficiency are considered key mediators of malnutrition-related immunosuppression induced by climate change, which increases the susceptibility of these individuals to fungal diseases.

(Swaminathan et al. 2014)



(Nnadi and Cater 2021)



Ex. 7: The threat of climate change to food security has contributed to adaptive agricultural practices with a increased use of fungicides. **Acquired azole resistance in *Aspergillus fumigatus* that is partly driven by the use of environmental fungicides is becoming increasingly problematic during treatment of aspergillosis in humans.**

Climate change



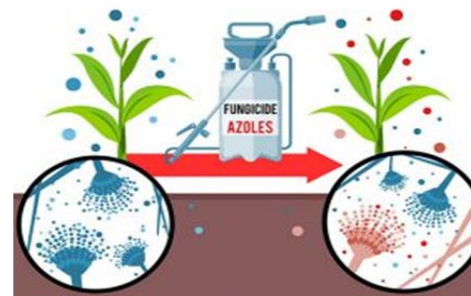
Increase of fungi and
mycotoxins contamination



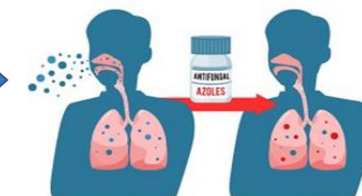
Intensive use of azoles in
crops to avoid toxigenic
species



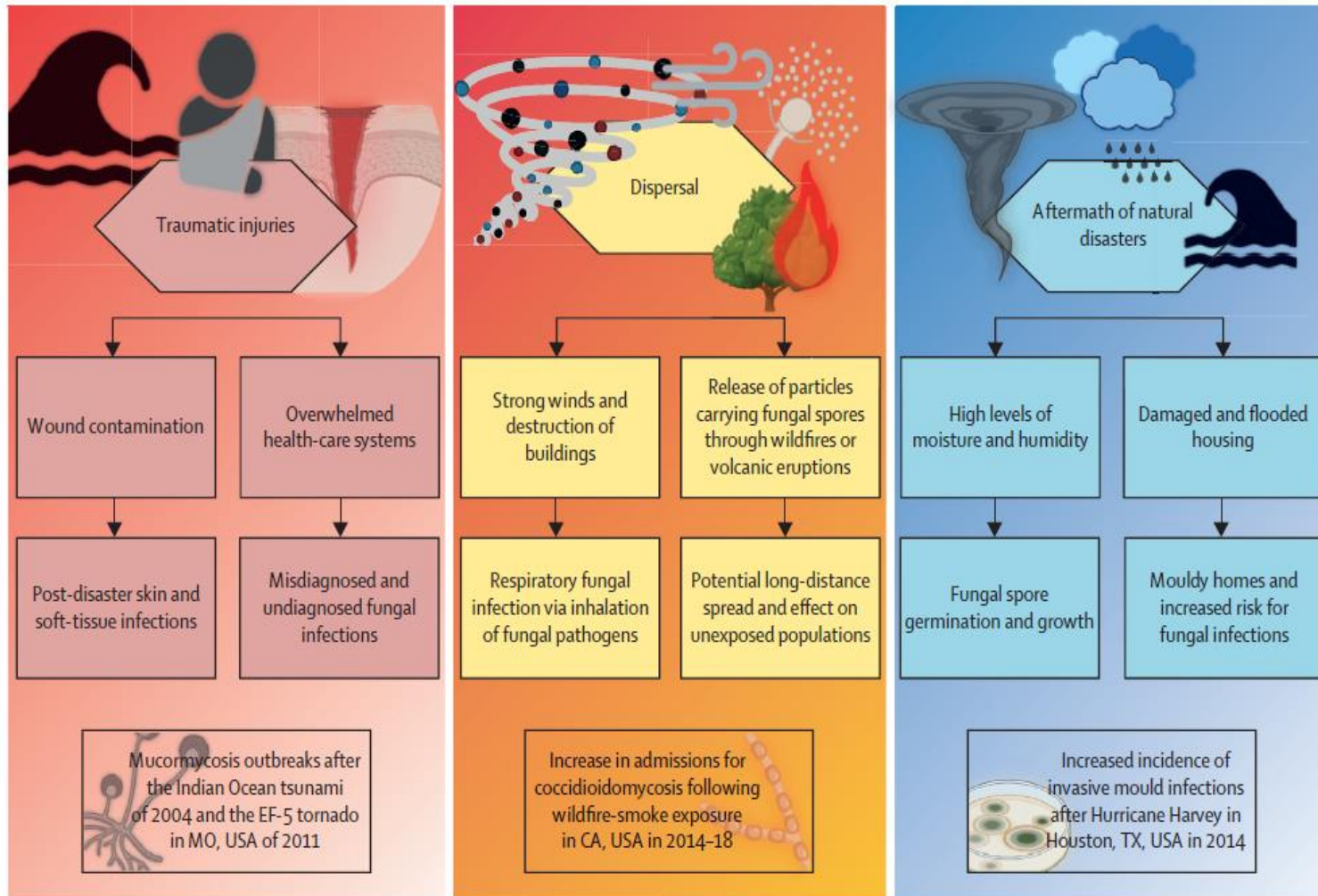
Resistant species can multiply
and survive (*A. fumigatus*)



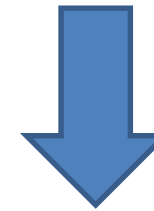
Infections are hard to treat
and life-threatening.



3 – Natural disasters and fungal outbreaks



Climate change is triggering profound long-term effects on fungal ecosystems and increasing frequency and intensity of devastating natural disasters.

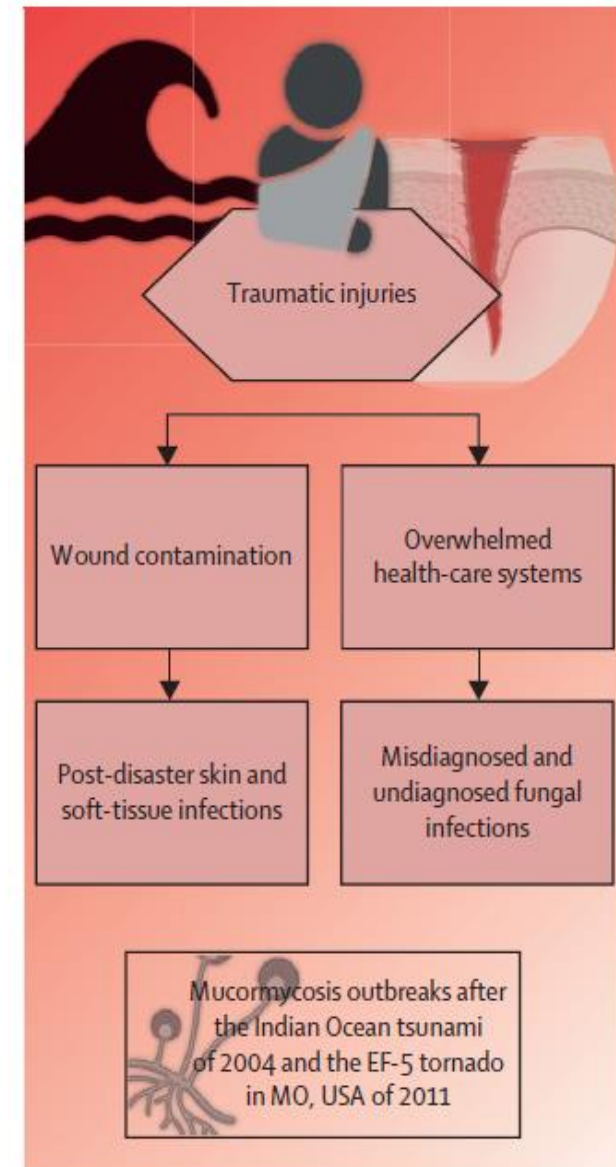


Outbreaks of fungal diseases

Mechanisms through which natural disasters trigger:

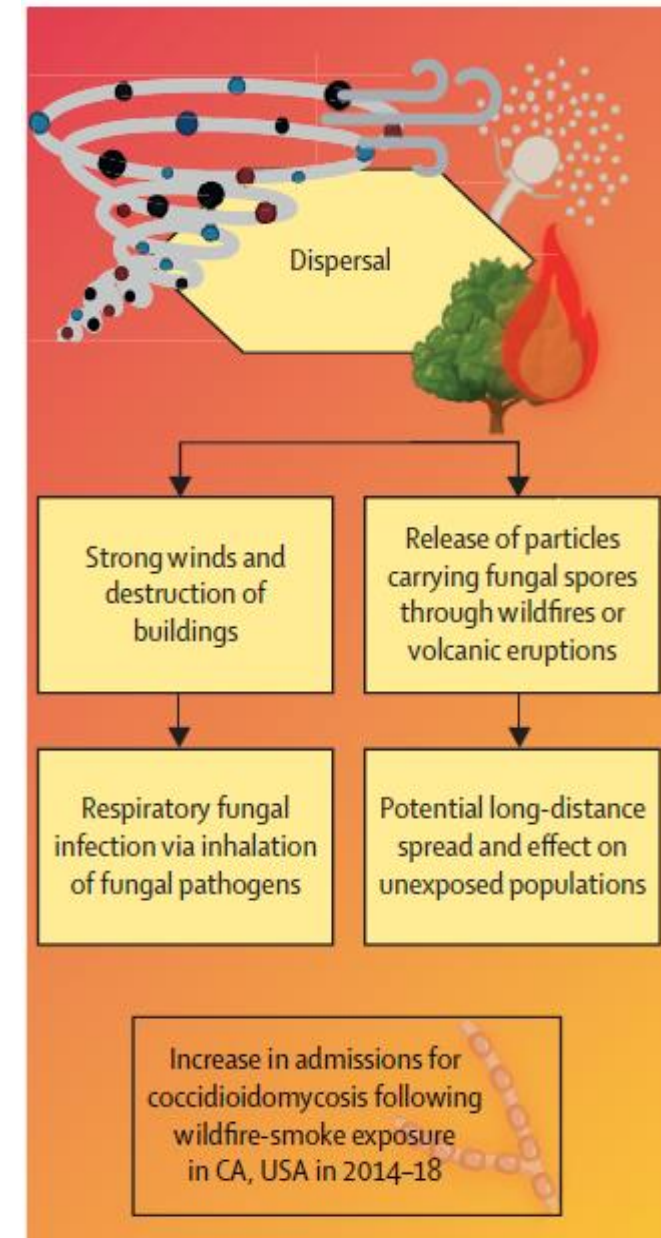
- **Natural disasters can cause extensive damage to natural habitats and urban areas, which can create conditions conducive to fungal growth or opportunities for fungal exposure.**
- **Natural disasters present a high risk for traumatic injuries, such as lacerations, abrasions, or contusions with disruption of the skin barrier, which provide entry routes for fungal pathogens.**

(Nelson et al. 2022)

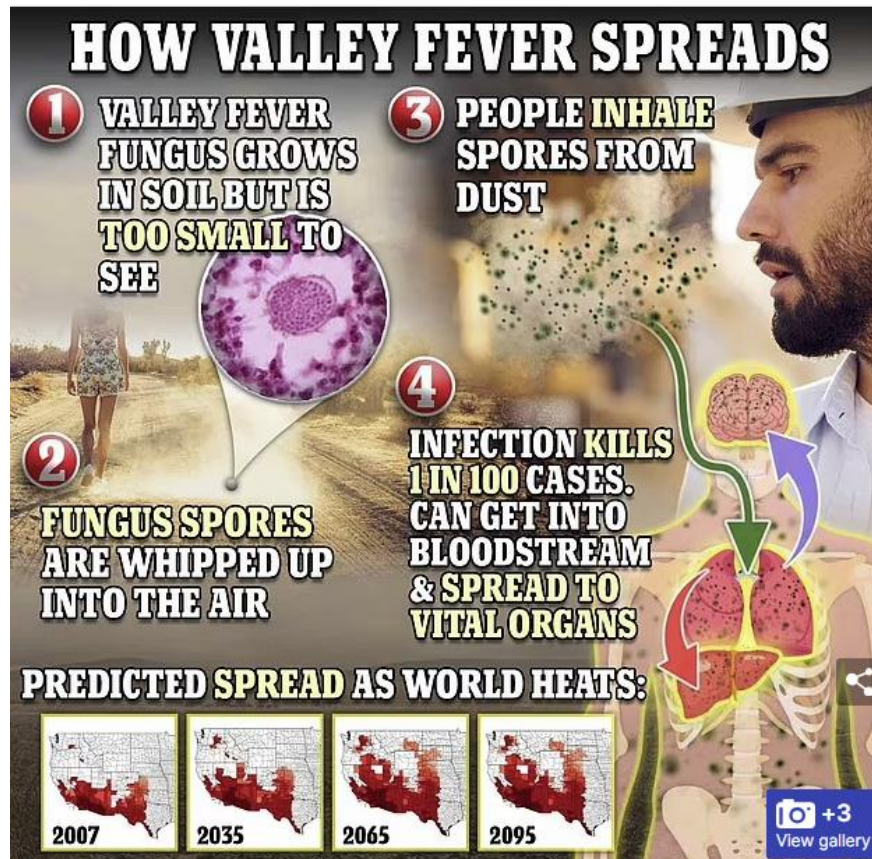


- **Wildfires and volcanic eruptions** leave ash that affects ecosystems **creating new niches for the colonisation of fungi** with functional traits that enable them to survive such extremes and cause harm to humans.
- **Widespread contamination with mycotoxin-producing moulds** **has also been reported after flooding events**, as high levels of humidity and moisture can cause fungal spores and biological fragments (such as mycotoxins) to become airborne and disperse across large areas, further facilitated by strong winds.

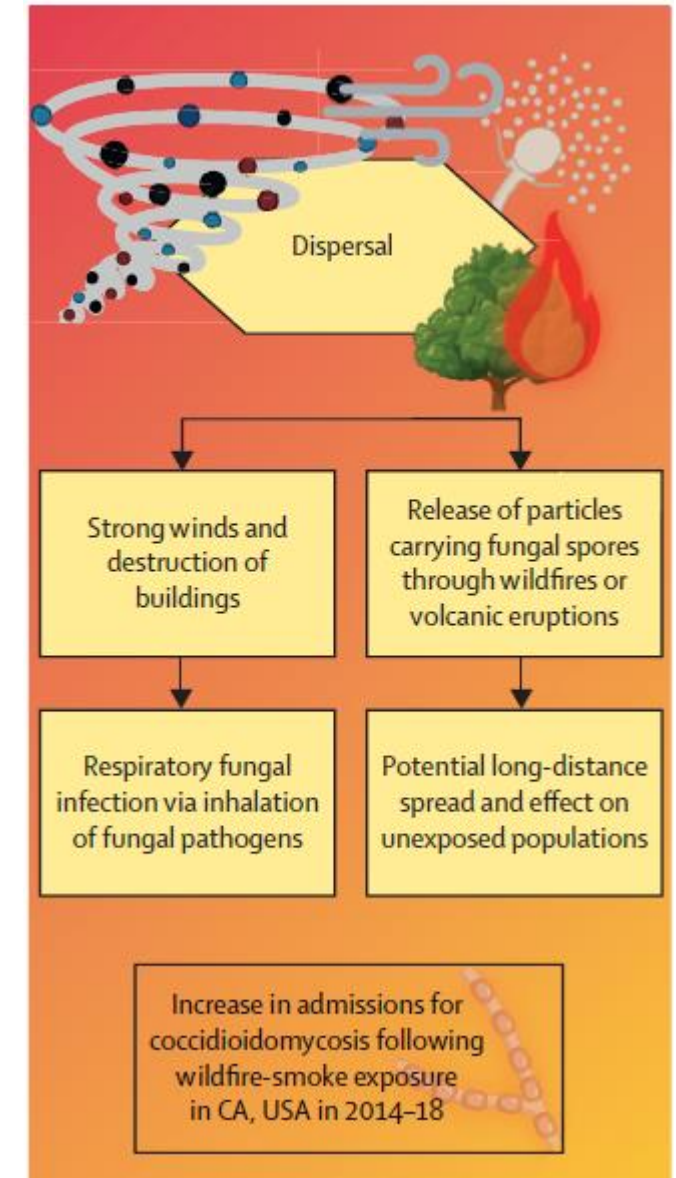
(Jaksic et al. 2020)



- Fungal spores can be carried over long distances through extreme storms or volcanic eruptions where **particles carrying fungal spores are released into the atmosphere.**



(Kobziar et al. 2020)



(Seidel et al. 2024)

- The dispersal of fungal pathogens following **building damage, storms, or wildfires** can cause **chronic inflammation, asthma, or respiratory fungal infections** through inhalation of fungal spores small enough to reach the alveolar surface of the lungs.

(Benedict and Park 2014)

- **Tsunamis, floods, and heavy rainfalls** can also lead to **marked increases in humidity and housing damage** in affected areas, providing conditions favourable for fungal germination and growth.

(Omebeyinje et al. 2021)

- **Tsunamis** might present a condition in which the land is seeded with **pathogenic waterborne microbes**.

(Engelthaler and Casadevall 2019)

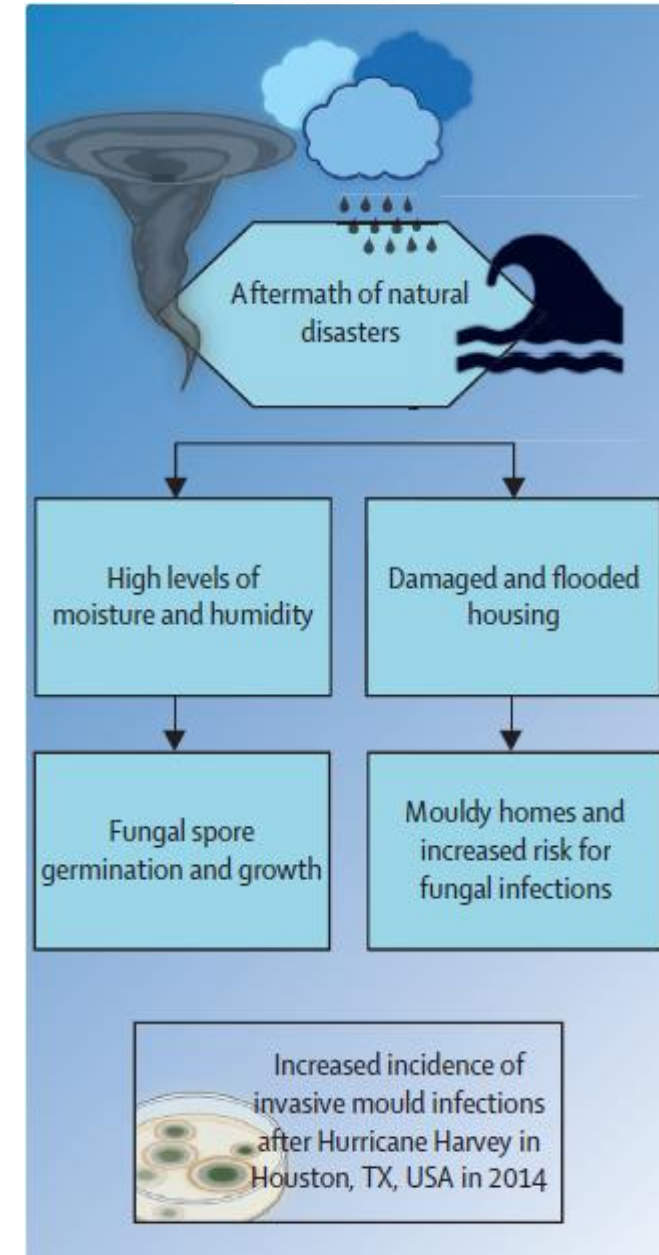


Table: Disaster-associated fungal infections*

Disaster	Reference	Location	No. cases	Fungal organism	Type of infection	Outcome
Tomado, 2011	Neblett Fanfair et al. (4)	USA	13	<i>Apophysomyces trapeziformis</i>	Soft tissue	38% all-cause mortality
Great East Japan Earthquake and Tsunami, 2011	Kawakami et al. (5)	Japan	1	<i>Aspergillus fumigatus</i>	Pulmonary, multi-organ dissemination	Death
	Nakamura et al. (6)	Japan	1	<i>Scedosporium apiospermum</i>	Lung and brain abscesses	Death
	Igusa et al. (7)	Japan	1	Pathogen not identified†	Sinusitis and meningitis	Death
Hurricane Ike, 2008	Riddel et al. (8)	USA	3	Unspecified agent of chromoblastomycosis	Soft tissue	Recovery
Hurricane Katrina, 2005	Rao et al. (9)	USA	1	<i>Cladosporium</i> sp.	Pulmonary	Resolved without treatment
Indian Ocean Tsunami, 2004	Petrini et al. (10)	Thailand	2	<i>Cladophialophora bantiana</i>	Soft tissue	Recovery
	Garzoni et al. (11)	Thailand	2	<i>Scedosporium apiospermum</i>	Spondylodiscitis, 1; brain abscess, 1	Recovery
	Gunaratne et al. (12)	Colombo, Sri Lanka	6	<i>A. fumigatus</i>	Meningitis	50% all-cause mortality
	Andresen et al. (13)	Sri Lanka	1	<i>Apophysomyces elegans</i>	Soft tissue	Not specified
	Snell and Tavakoli (14)	Thailand	1	<i>A. elegans</i>	Soft tissue	Recovery
	Maegele et al. (15)	Southeast Asia	1	<i>Fusarium</i> sp.	Soft tissue, sepsis	Death
		Asia	1	<i>Mucor</i> sp.	Soft tissue	Not specified
Earthquake, 1994	Schneider et al. (16)	USA	203	<i>Coccidioides immitis</i>	Pulmonary; 6 (3.7%) disseminated	1.5% all-cause mortality
Volcano, 1985	Patiño et al. (17)	Colombia	8	<i>Rhizopus arrhizus</i>	Soft tissue	80% all-cause mortality
Dust storm originating near Bakersfield, California, 1977	Flynn et al. (18)	USA	115	<i>C. immitis</i>	Pulmonary; 16 (14%) disseminated	7% all-cause mortality
	Williams et al. (19)	USA	18	<i>C. immitis</i>	Pulmonary; 4 (22%) disseminated	5.5% all-cause mortality

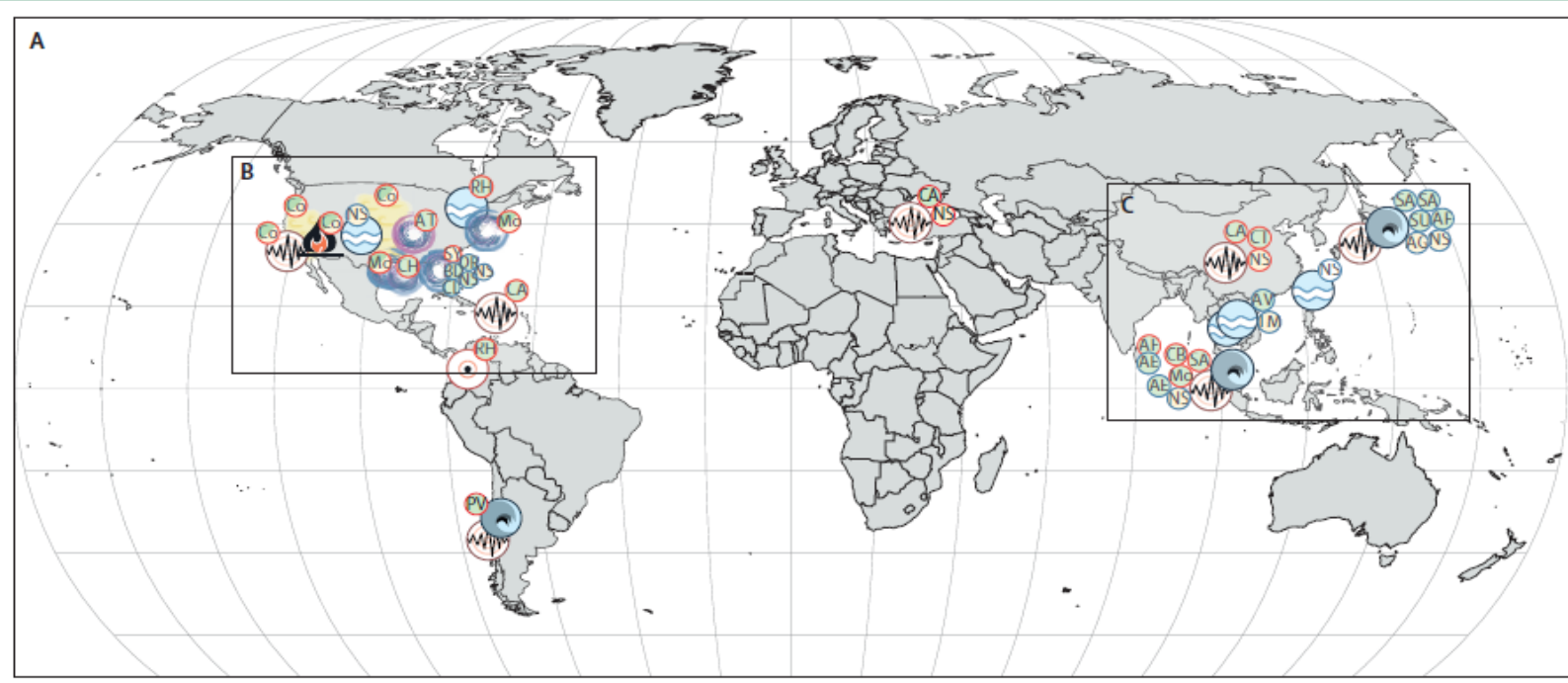
https://wwwnc.cdc.gov/eid/article/20/3/13-1230_article

Fungal infection have been related with climate adverse events due to climate changes.

CC could be affecting the ecology of pathogenic fungi in ways that are not yet fully understood.



Even minor or gradual changes in temperature, moisture, and wind patterns might affect fungal growth, distribution, and dispersal.



A match in the geographical distribution of reports of natural disaster-associated fungal outbreaks



The geographical distribution of natural disasters



Fungal outbreaks following natural disasters are likely to be under-reported

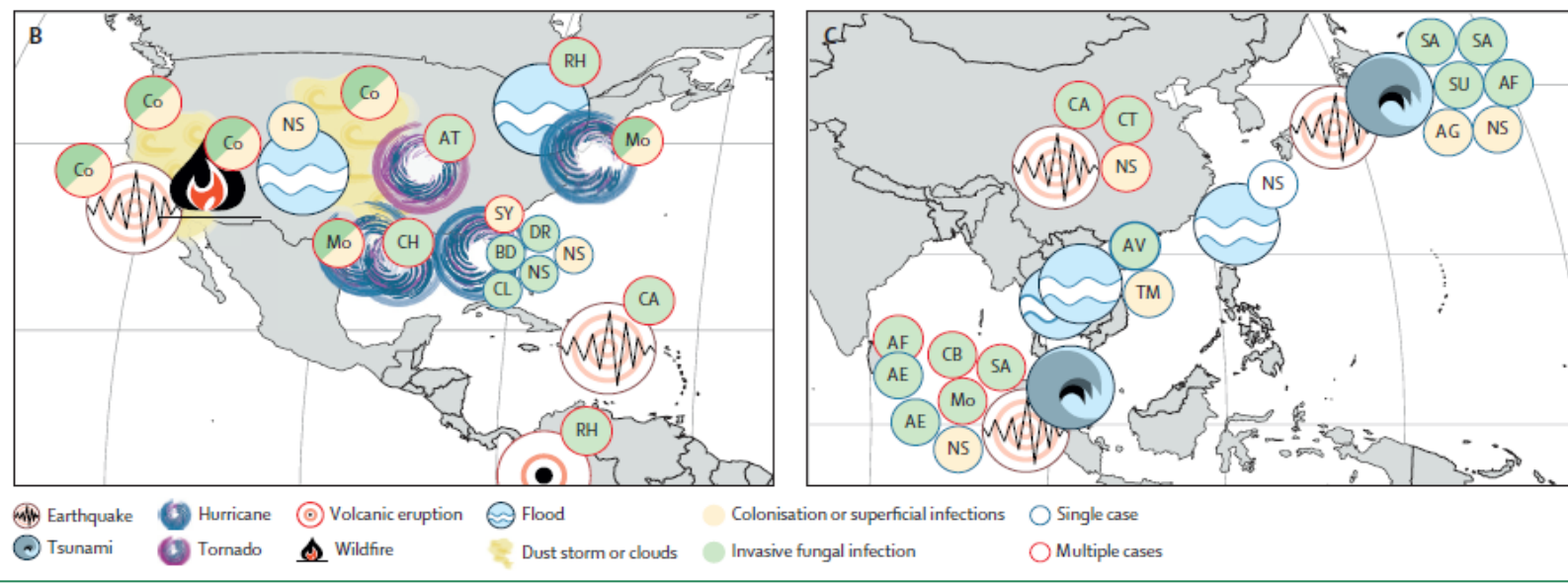


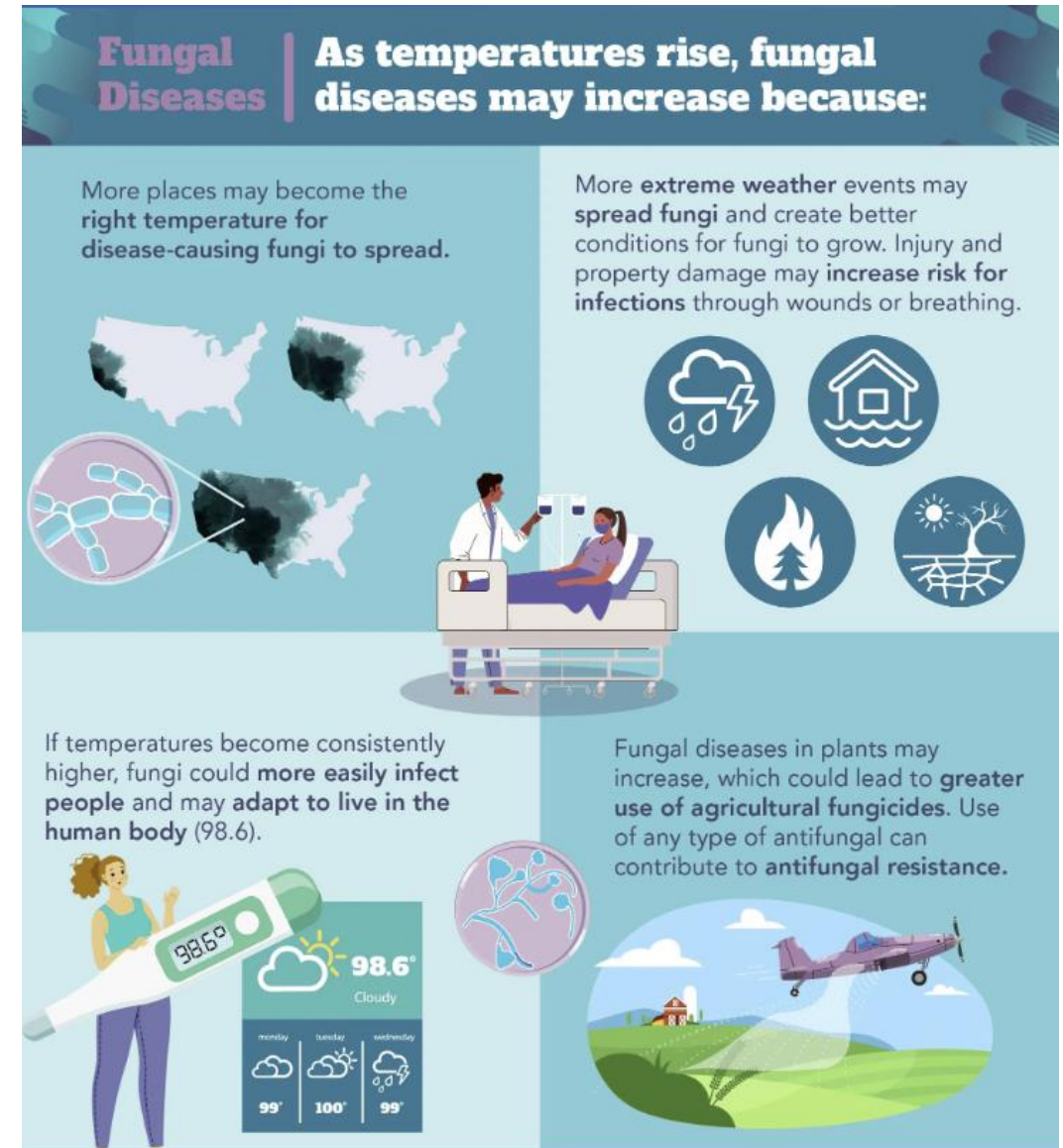
Figure 4: Global distribution of fungal outbreaks related to natural disasters
 (A) World map. (B) North and middle America. (C) Southeast Asia. AE=Apophysomyces elegans. AF=Aspergillus fumigatus. AG=Aspergillus glaucus. AT=Apophysomyces trapeziformis. AV=Aspergillus flavus. BD=Blastomyces dermatitidis. CA=Candida albicans. CB=Cadophialophora bantiana. CH=unknown (chromoblastomycosis). CL=Cadosporium spp. CT=Candida tropicalis. CO=Coccidioides immitis. DR=Drechslera spp. Mo=moulds. NS=not specified. RH=Rhizopus arrhizus. PV=Paeclomyces variotii. SA=Scedosporium apiospermum. SU=Scedosporium aurantiacum. SY=Syncephalastrum spp. TM=Trichosporon mucoides.

Underreporting could be attributed to several factors:

- **challenges in conducting research in disaster-affected regions** (where health-care facilities operate at reduced capacity), when the primary focus is on immediate health concerns.
- **diagnosis of invasive fungal disease might be compromised by a scarcity of appropriate diagnostic tools and professionals trained in mycology** as well as little awareness and knowledge regarding the epidemiology of invasive fungal diseases following natural disasters
- **misdiagnosis, the absence of diagnosis, and the absence of validated invasive mould infection case definitions** could result in their exclusion from systematic reporting.
- **low research funding** can further hamper systemic documentation of fungal diseases in the setting of natural disasters.

To reduce the devastating impact of natural disaster associated fungal outbreaks is important to:

- monitor fungal exposure following natural disasters
- perform risk assessment as well as short-term and long-term remediation efforts





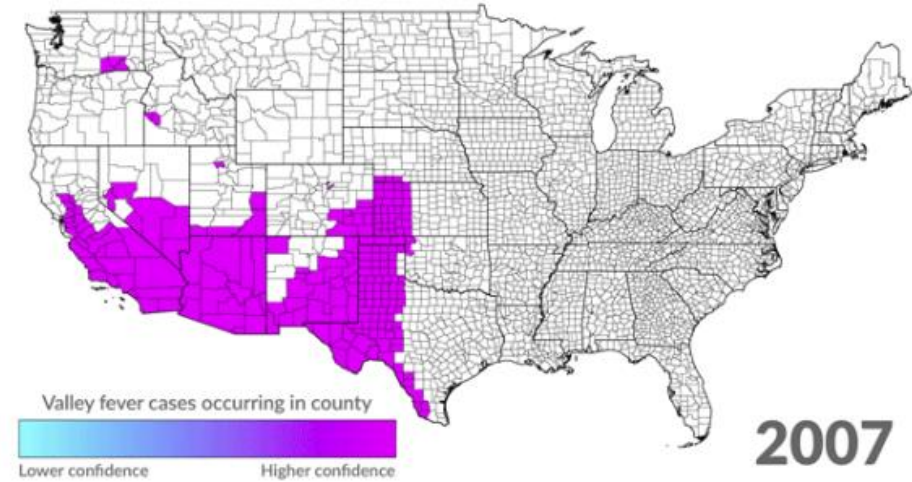
The changing climate has promoted the:

- Spread and acquisition of fungal diseases
- Emergence of new fungal pathogens
- Increased dispersion of fungi

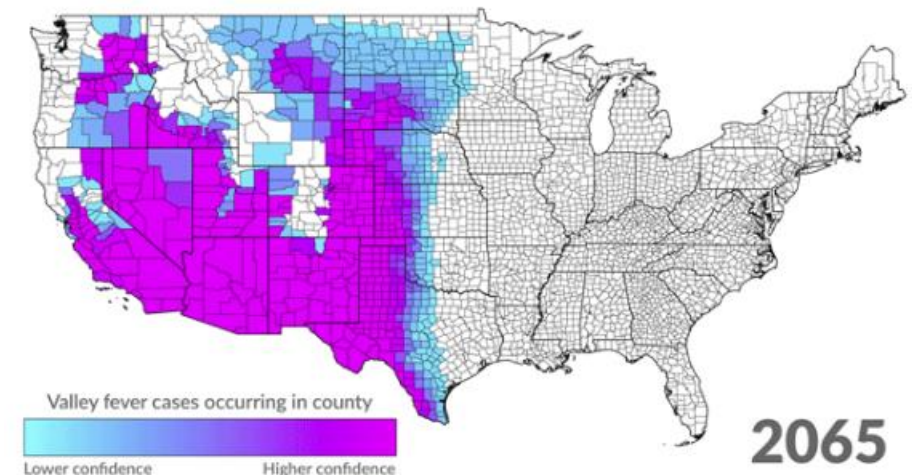
To sum up:

- **Fungi are becoming more thermotolerant**, resulting in the emergence of new species that are pathogenic to humans.
- **Several fungi**, once confined to specific regions, **have emerged as major health threats in areas unaccustomed to such infections.**
- **Climate change** has also been associated with water supply and food scarcities owing to its **adverse effects on crop yields and agricultural productivity.**

Expansion of Valley fever in the western US
in response to high climate warming (RCP8.5)



Expansion of Valley fever in the western US
in response to high climate warming (RCP8.5)

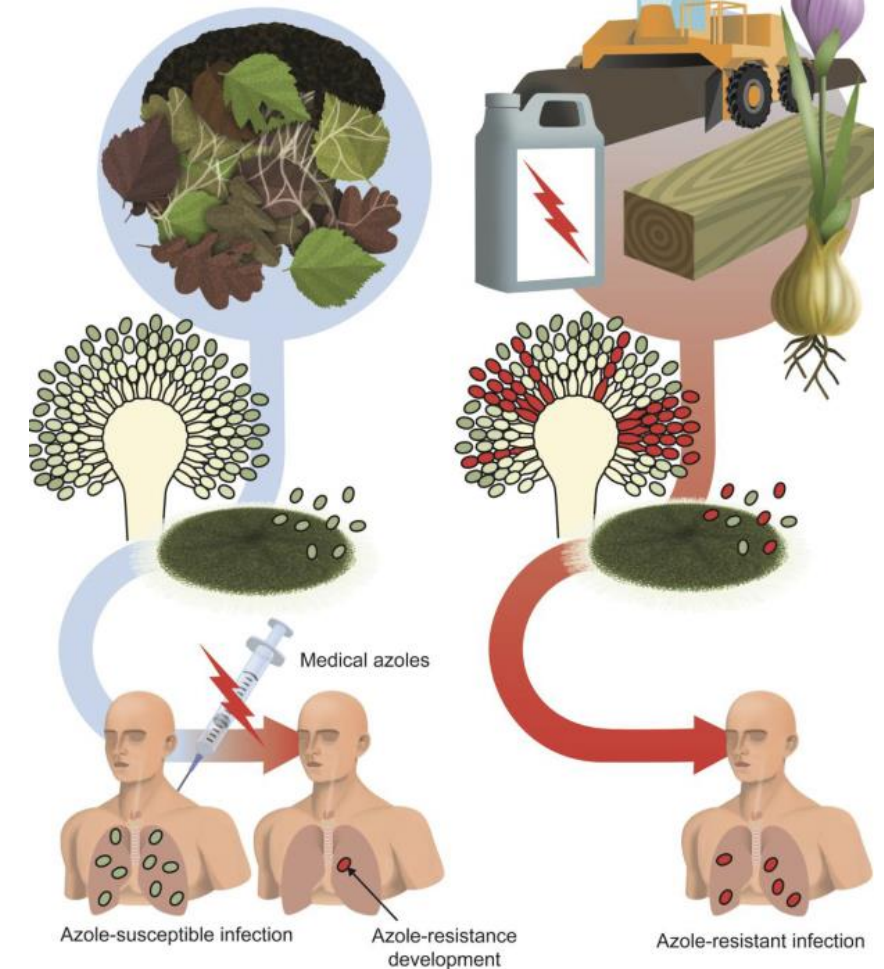


Hotspots azole-resistant *A. fumigatus*
with regard to origins, increase and spread

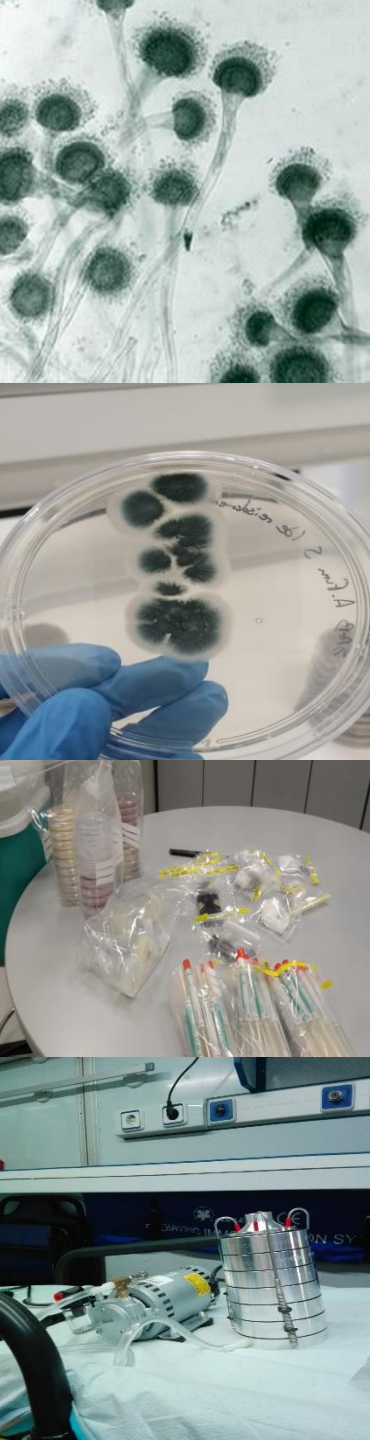
1. Favorable growth conditions
2. Completion of life cycle
3. Presence of azoles

Natural environment

Azole-containing environment

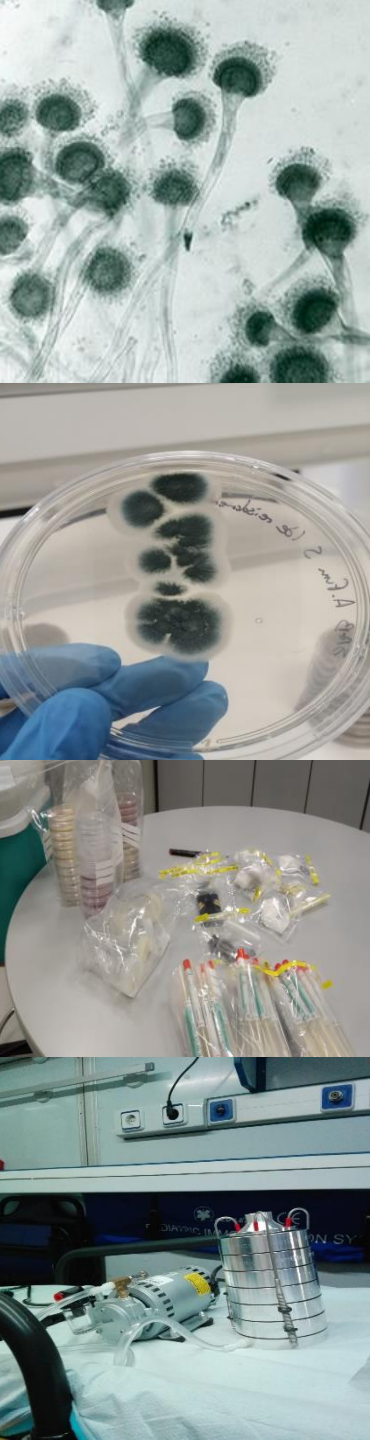


- The increased reliance on fungicides to protect crops continues to increase and might contribute to the development of antifungal resistance in fungal pathogens, representing a crucial One Health problem and posing a major threat to both agriculture and human public health.
- Factors such as traumatic injuries during disasters, along with the weakened immunity and health of displaced people, provide favourable conditions for fungal pathogens and substantially increase the susceptibility of populations to fungal infections.



4 – Main conclusions

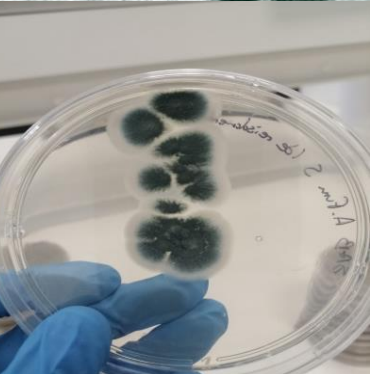
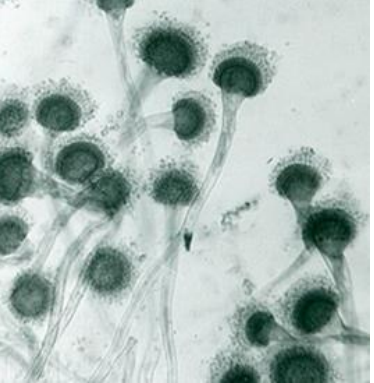
- Awareness from **WHO** and **EU**
- International and national **legal framework**
- Exposure (occupational) leads to **health outcomes**
- **Climate change is impacting on fungal diseases**
- **Natural disasters are drivers of fungal outbreaks**



The impact of climate change on fungal pathogens and diseases, exacerbated by natural disasters and population displacement due to climate change, is an urgent global issue affecting all countries.

Systematic and collaborative global efforts to:

- mitigate the deleterious effects of climate change
- increased understanding of the inter-relatedness between climate change, natural disasters, and fungal infections
- improve efforts in terms of prevention, detection, and treatment.



Thank you for your attention!!

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