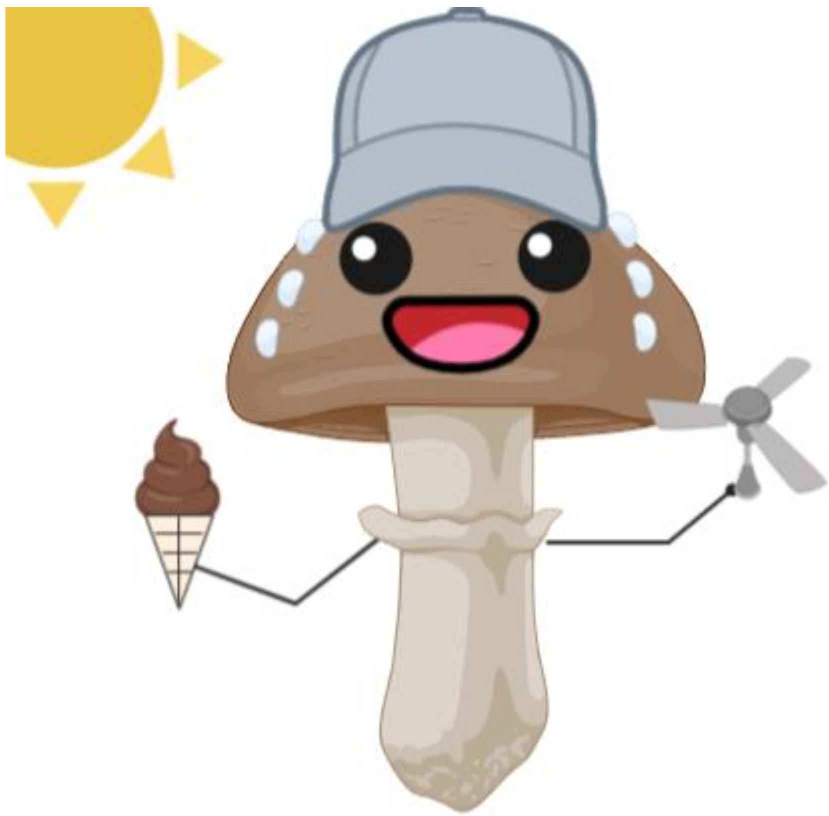
Mushroom Sweat: How Fungi Stay Cold

Teacher, why do we sweat?



Humans, plants, and fungi all sweat to cool down.
This is how a mushroom might stay cool if it did the same things kids do!

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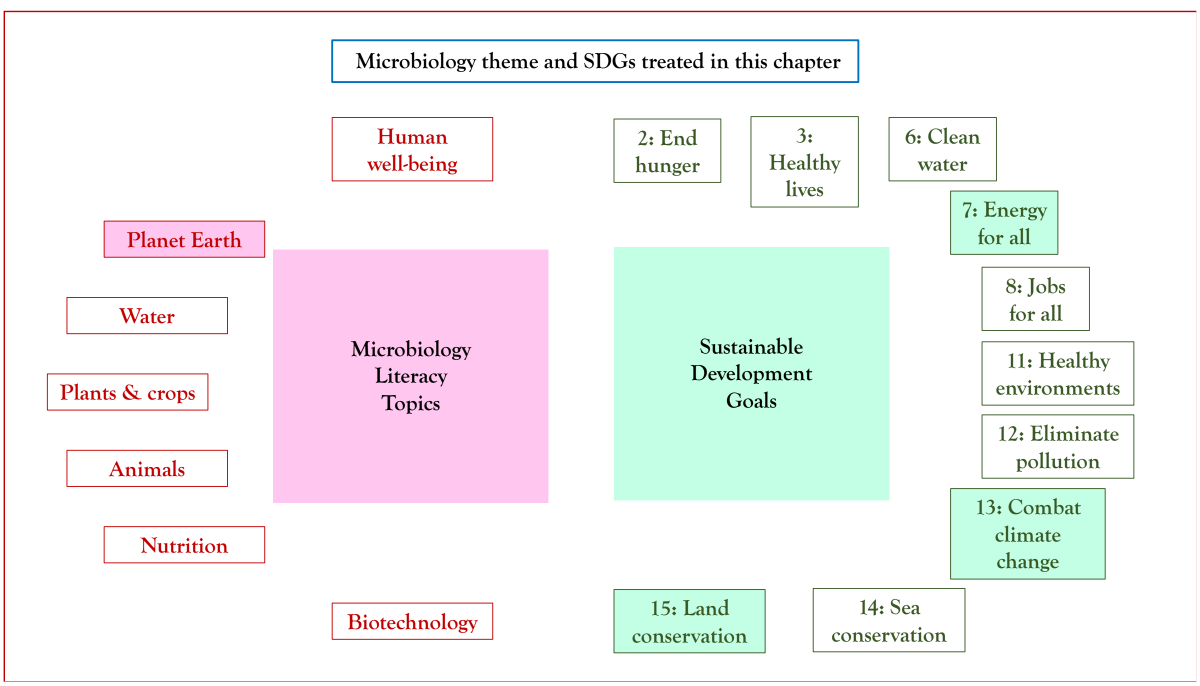
Fungi Sweat

Storyline

When our body temperature rises on a hot day, from a fever, or from exercise, we sweat to keep our temperature at a comfortable 98.6 degrees Fahrenheit /37 degrees centigrade. As sweat on the skin evaporates to the air, it removes heat in a process known as evaporative cooling. Humans are not the only organisms that sweat to cool down. Plants also release water through microscopic pores on their leaves to remove excess heat. Fungi, a diverse and versatile kingdom of life that includes mushrooms, molds, and yeasts, also "sweat" to cool both the fungus and the area around it. Experiments using thermocouple detectors and thermal imaging have shown that mushrooms, molds, and yeasts are colder than their surroundings, also via evaporative cooling. The water droplets that form over mold and yeast colonies grown in Petri dishes, suggests that "sweating" is a cooling mechanism used throughout the fungal kingdom. The observations that mushrooms can cool the surrounding air suggests that fungi can play a role in keeping their environments cooler, whether that environment be a forest floor or a windowsill. Could mushrooms and other life forms that undergo evaporative cooling have the potential to help households save energy and prevent climate change? In summary, sweating is a common way for living organisms to maintain comfortable temperatures, and fungi's properties give them vital roles in today's ecosystem.

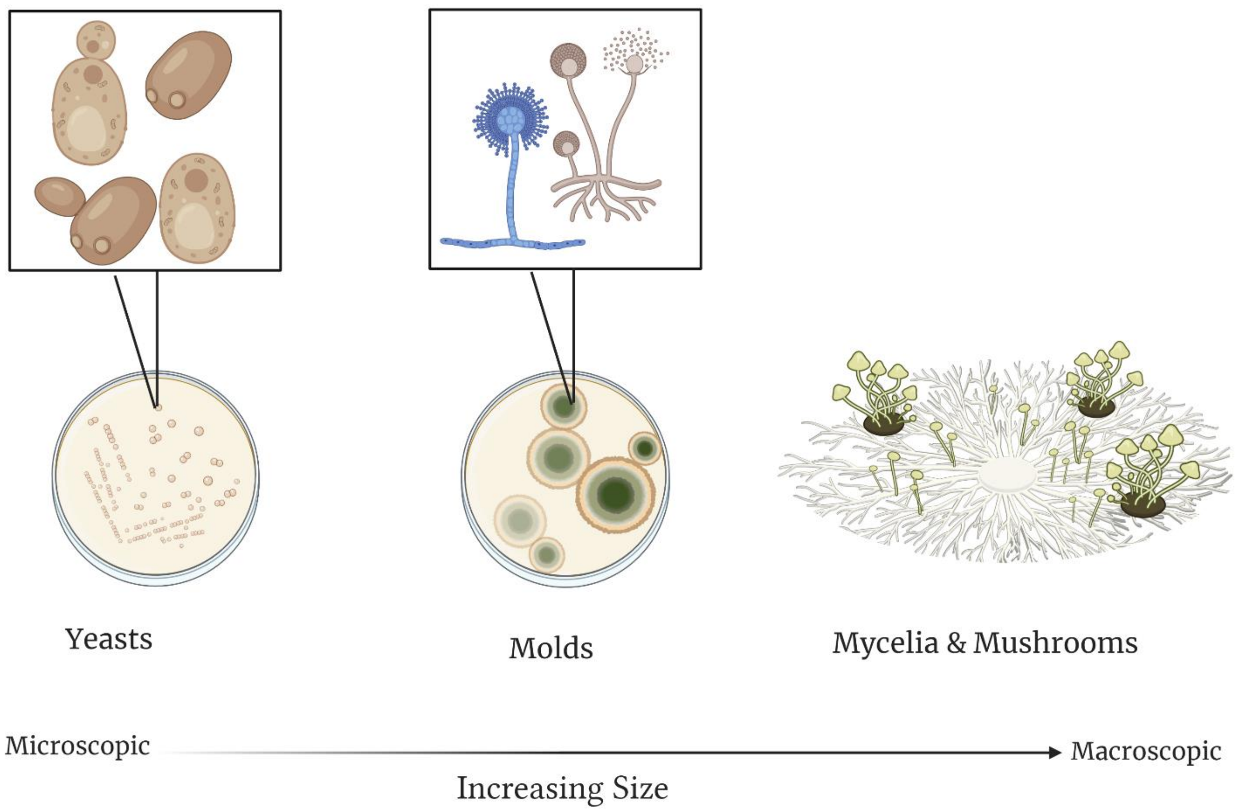
The Microbiology and Societal Context

The microbiology: microbial fungi; microbial ecology; microbial thermoregulation; adaptations; transpiration; biogeochemical cycles. *Sustainability:* climate change; energy conservation; sustainable energy.



Fungi Sweat: the Microbiology

1. Scientists discovered fungi are relatively cold using the scientific method. Fungi make up a distinct kingdom of life that are neither animals nor plants. It includes everything from the microscopic yeast in bread to the molds that grow on rotten fruit and the mushrooms on the sidewalk (*see further reading resources for more information about the diversity of this kingdom)*. Mushrooms are the fruits of fungal mycelia that live underground or inside trees, just like an apple is the fruit of a tree. An apple produces seeds that grow into more apple trees, and mushrooms produce spores that grow into more fungal mycelia.



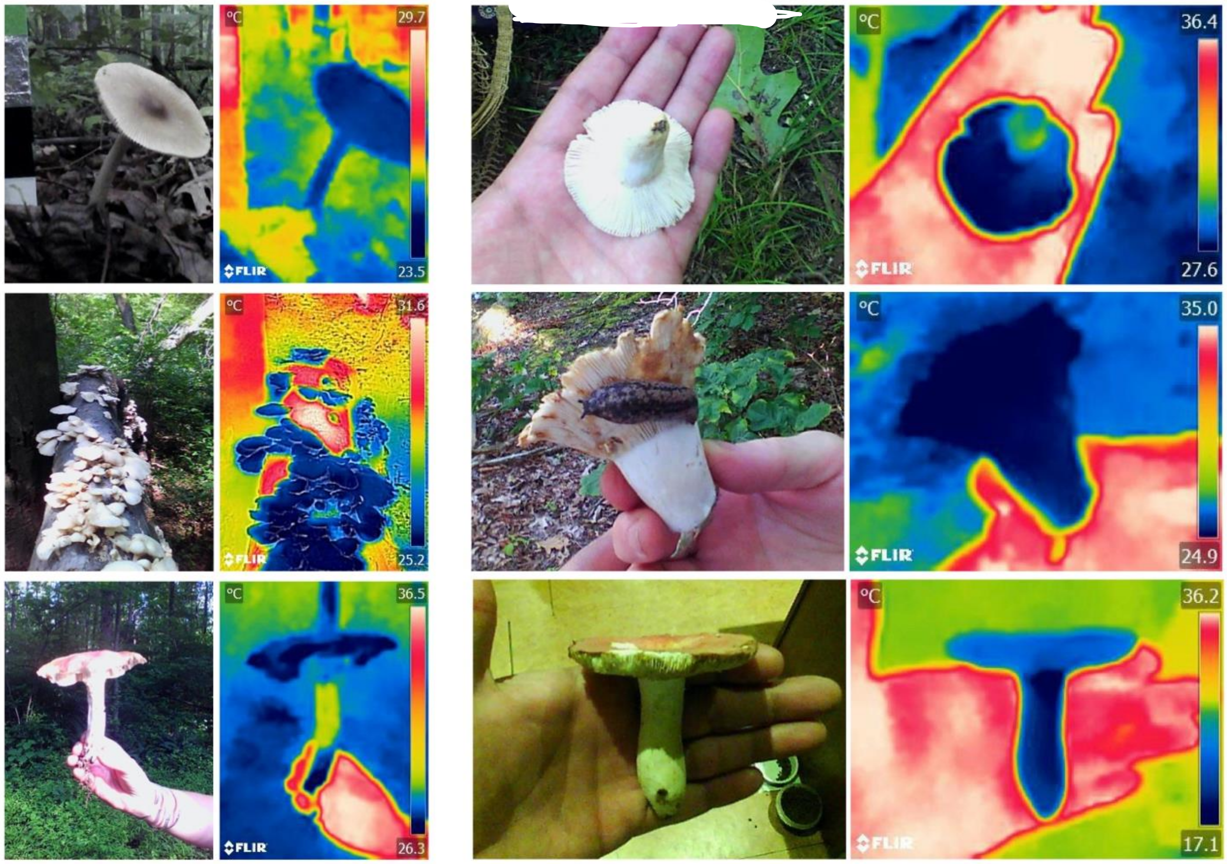
A Visual of Different Fungal Life Forms: Yeast, Molds, and Mushrooms.

The ability of fungi to cool themselves and their surroundings was first a hypothesis or an educated guess. The idea then was supported with experiments to support or refute it, three of which are outlined here. In one experiment, metal thermocouples inserted inside mushrooms recorded significantly lower temperatures than the surrounding air (*see the article Evaporative Cooling of Mushrooms for a more advanced overview of the experiment)*.

The second experiment used a thermal camera, a device used to measure temperatures based on the amount of radiation emitted by an object. The typical cameras in our phones detect the light our eyes can see (known as visible light). However, a thermal camera uses a microbolometer to detect infrared light, a type of invisible light that is emitted by all matter. According to the Stefan-

Boltzmann Law of Radiation, warmer objects emit more infrared radiation. (*see the UTexas YouTube video on blackbody radiation for more information on this topic*).

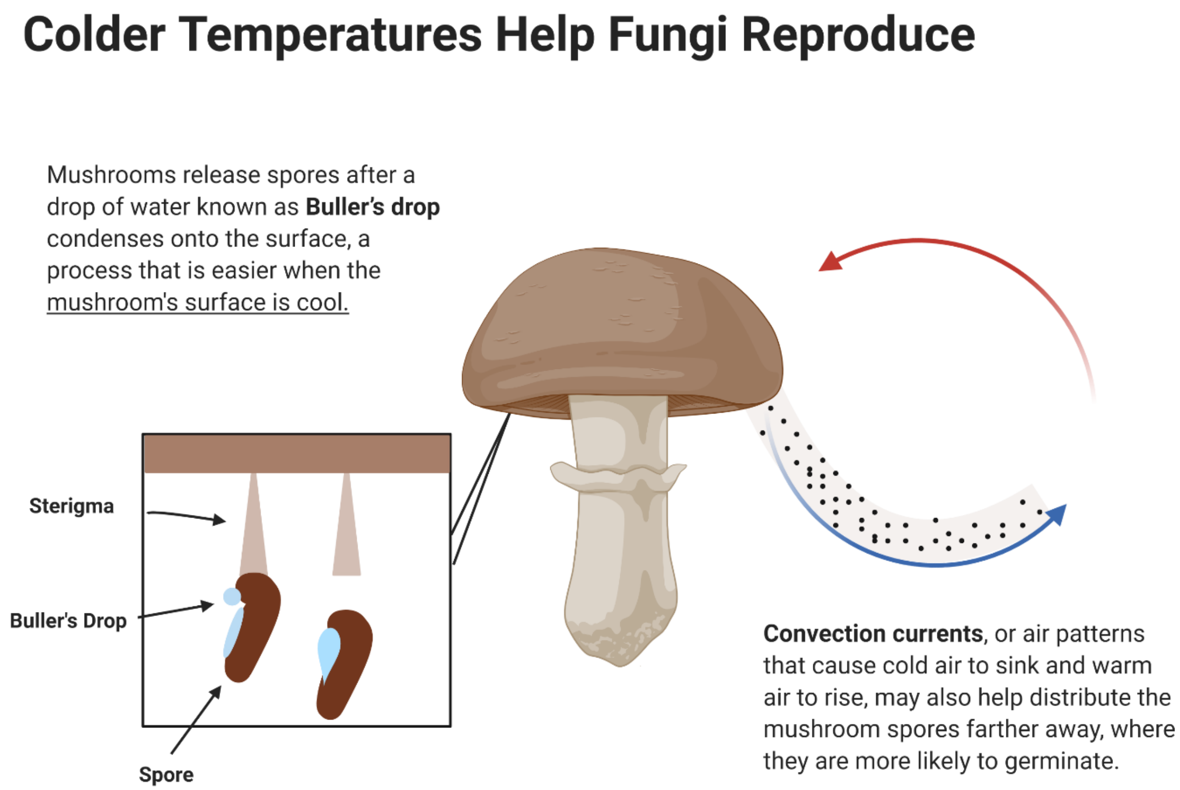
With the knowledge that infrared radiation and temperature are related, scientists took thermal images of various fungi species. Most of the species captured on camera emitted less thermal radiation and appeared colder than their environments. (*see the paper Fungi are colder than their surroundings by Cordero et al for a more detailed overview of these concepts)*. Together, these observations suggest that fungi are relatively cold organisms.



An example of infrared and visible images various wild mushrooms. Note the scale bar right of the images shows which colors correspond to which temperatures. See the YouTube video on *Amanita muscaria* for another example of thermal imaging.

2. Why are fungi colder than their surroundings? There are several ideas as to why fungi are colder than their surroundings, all of which assume that a colder environment must have some sort of advantage to the fungus. Otherwise, why would the fungus expend space and energy with structures to keep it cold?

One idea is that cool temperatures are important for fungal reproduction. Remember that just as plants use seeds to reproduce, mushrooms use spores. Mushrooms release spores after a drop of water, known as Buller's drop, condenses onto the surface, a process that is easier when the surface is colder than the surrounding air (think about the water droplets that form on the outside of a glass containing a cold drink). In addition, convection currents, or air movements resulting from the tendencies of cold air to sink and warm air to rise, and caused by temperature differences of different objects and air in a given space, will be created by fungi being cooler than their surroundings and may help to disperse the spores to locations far away, where they are more likely to germinate. In addition to mushrooms, studies show that yeast also tends to sporulate better at colder temperatures (*see the paper Fungi are colder than their surroundings by Cordero et al for a more detailed overview of these concepts)*.



A diagram summarizing why mushrooms prefer cooler temperatures. Fungi reproduce via the release of spores. Mushrooms are specialized structures for the production and release of spores. It is believed that the cold temperature of mushrooms is important for spore release. Spores get detached from the mushroom's gills by the pressing weight of a water droplet (Buller's drop) that condenses on top of the spore. This condensation occurs when the moist air touches a cooler surface, hence, the cold temperature of mushrooms contributes to spore release and fungal reproduction.

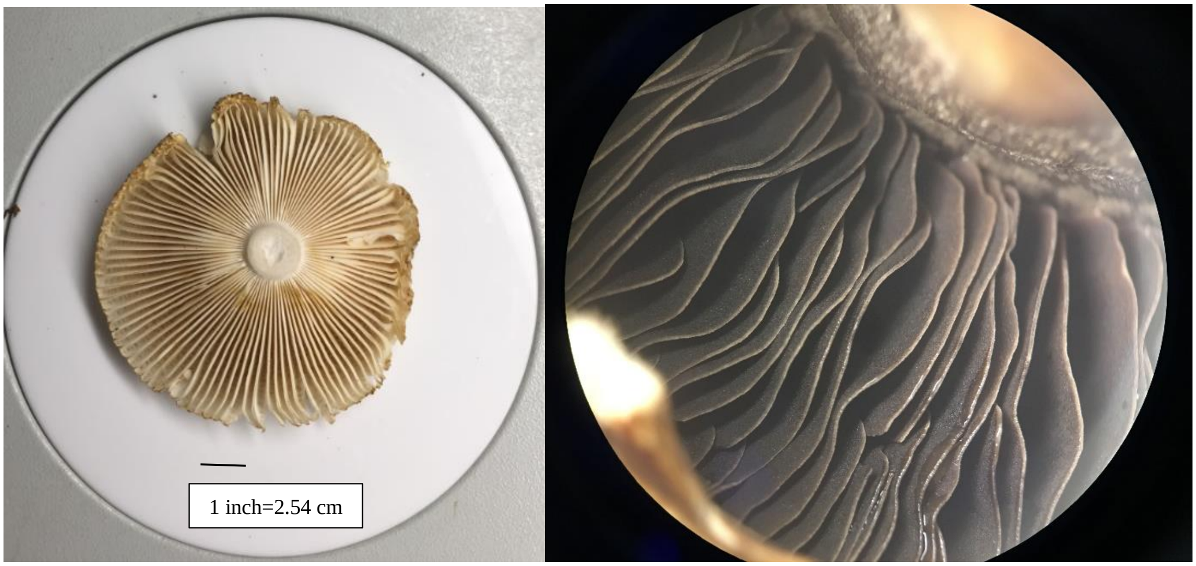
3. Sweating cools organisms down. What we call "sweating" is a natural human response to overheating in which perspiration makes its way to the surface of the skin. This perspiration, or human sweat, is mostly water with some salt. When this water evaporates (changes from liquid to gas), it absorbs heat from the surroundings. By absorbing heat as it evaporates, the perspiration cools us down (*see the Kids' Health article for an overview of why we sweat*). A helpful analogy would be how people sometimes feel cold after they get out of a pool; as the water droplets on our skin evaporate, they remove heat, resulting in a cooling effect. The method in which an area cools down when a liquid transforms into a gas is known as evaporative cooling, and it is the physical process that allows sweat to cool us down.

Humans are not the only organisms using this method to keep cool. If you have ever been on a picnic, you know that often you would rather sit under a tree than out under the sun. This is not just because of the shade; trees are cooling their surroundings through a similar process. In plants, the process is also known as transpiration, where water (essentially plant "sweat") leaves the plant through pores known as stomata (sing. stoma) to cool the surroundings (*see the ScienceMag article for more information)*. Both human perspiration and plant transpiration cause evaporative cooling, which helps regulate their temperatures.

4. Fungi stay cool and can make their surroundings cooler via evaporative cooling. Generally, mushrooms prefer to grow in areas with plenty of water nearby (think forest over desert). You may be familiar with the phrase "like mushrooms after the rain," which describes how after heavy rainfall mushrooms tend to appear. While evaporative cooling is advantageous, in terms of temperature control, it involves loss of water that needs to be replaced. Most cells/most forms of life consist mostly of water, so we need to have a good supply of water. Insufficient water is one of the most prevalent forms of stress confronting organisms, especially under warm conditions requiring evaporative cooling. Therefore, wet and humid areas offer the perfect habitats for mushrooms to grow and spread reproductive spores. This preference for areas with water may be because fungi also undergo evaporative cooling just like humans and plants do. Thus, we can *technically* say that fungi do "sweat."

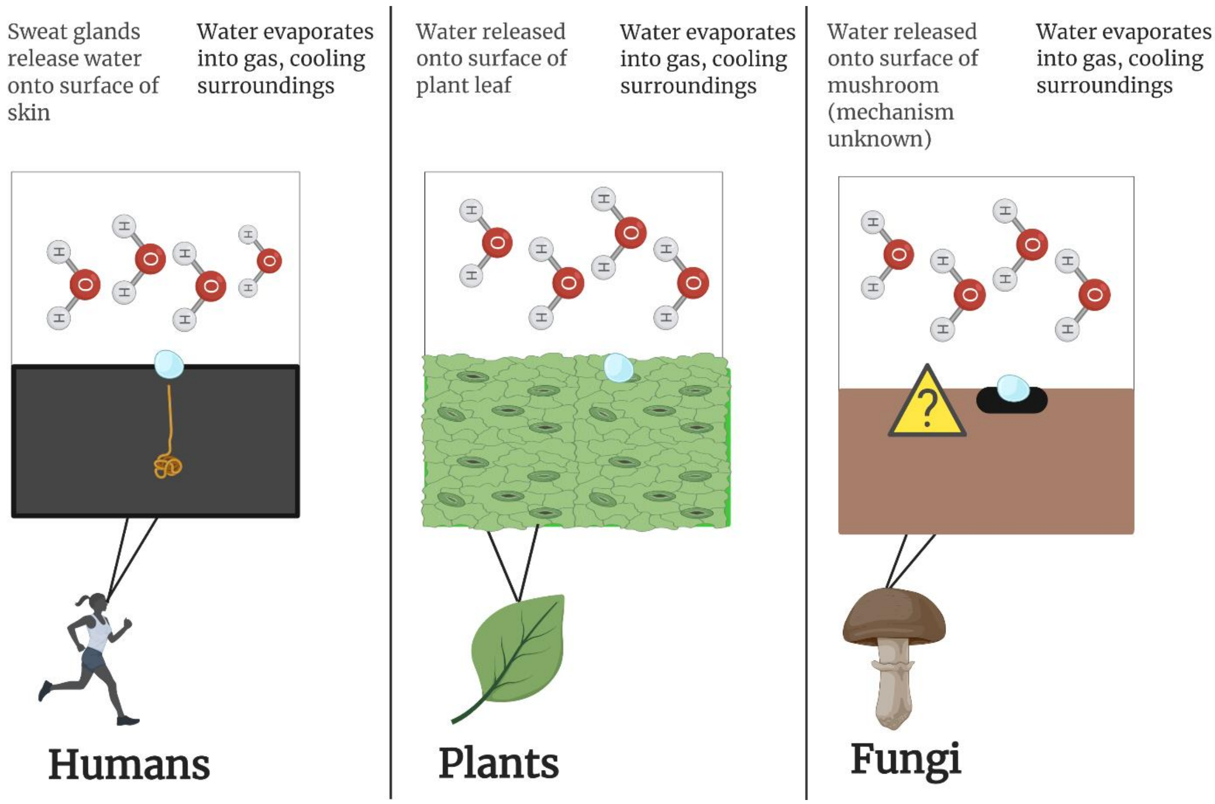
Evaporative cooling in mushrooms was discovered when scientists observed that mushrooms cooled down when the air was blown on them. Think back to the image of how people are cold when they get out of the pool in part three. If you got out of the pool, you would be even colder if it were windy outside because of evaporative cooling. This led scientists to believe that mushrooms were undergoing a similar process (*for more advanced reading, look at Evaporative Cooling of Mushrooms for a more thorough explanation)*.

Another experiment grew yeasts and molds on sealed plates in a laboratory. Scientists observed water beading on the lids of the plate, indicating that it had evaporated from the biofilms in question from yeast cooling themselves down. Both experiments support the hypothesis that fungi also use evaporative cooling to regulate their temperature (*see the paper Fungi are colder than their surroundings by Cordero et al for a more detailed overview of these concepts)*.



A visual of how mushroom gills (L: unidentified, R: *Agaricus bisporus*) increase the organism's surface area.

A fungus undergoes evaporative cooling thanks to their high-water content and their large surface area. The high water content means that mushrooms have plenty of water that can be evaporated. A large surface area increases the potential for exchange with the environment and increases evaporative cooling abilities in plants as well. In looking at a tree, several small leaves might cool the tree more effectively than one large leaf. If you look at the underside of an edible button mushroom (or at the images above), you can see or feel several soft ridges that are called gills. These folds increase the mushroom's total surface area 10-20-fold, further increasing its capacity to cool its surroundings (*see the paper Fungi are colder than their surroundings by Cordero et al 2020 for a more detailed overview of these concepts)*

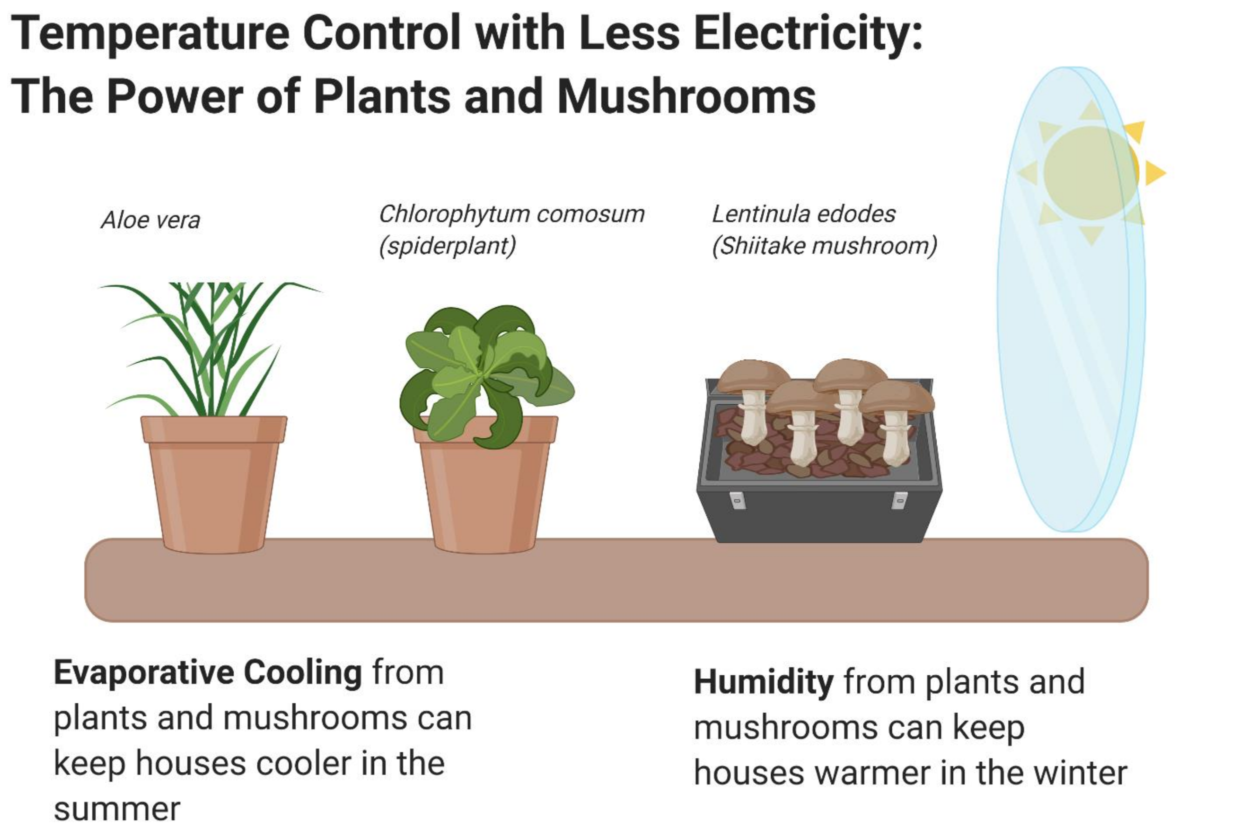


A diagram summarizing evaporative cooling in humans, plants, and mushrooms. Water is exported to the surface of humans and plant leaves via sweat glands and stomata, respectively. Scientists are still trying to see how water is transported to the surface of mushrooms.

5. Could fungi and other living organisms be used to cool our homes with less electricity?

Sometimes people will talk about purchasing plants such as Aloe vera or spider plants to cool down their house without cranking up the air conditioning. Mushrooms, and truly any organism with significant water content, create a similar effect due to their evaporative cooling properties. Even though a single plant may not be able to completely replace an air-conditioning system as of now, growing fungi and plants in our home can help us use less air-conditioning and conserve electricity, thus reducing our carbon emissions and power bills. Plants and fungi also have a purpose in the winter months too!

Evaporative cooling also increases the humidity of the surrounding environment. In winter, our heating systems reduce humidity, producing drier air that tends to dry our eyes, mouths and noses and makes us uncomfortable. Moist air is not only healthier for us but also tends to make a room feel warmer. Thus, the indoor cultivation of these specimens may make us feel better and help us save money and energy on heating in cold weather, as well as cooling us in warm weather (*see the San Francisco Chronicle article for another overview of this concept)*. See the Appendix for information on how to make your own mushroom-powered "air conditioner."



A diagram summarizing how plants and mushrooms can contribute to controlling temperatures in a household.

6. ***Fungi and other microbes play an important role in fighting climate change.*** Oftentimes, we think the biggest battlers of climate change are larger plants and trees, but microbes have a place at the table as well. The carbon cycle is the process where carbon cycles from humans to plants, and unfavorably, into the atmosphere by industrial activity. Plants have an incredible capacity to take up carbon from the atmosphere for photosynthesis, but they are not working alone. Microscopic fungi, usually as symbionts in a relationship known as mycorrhizae, enhance carbon absorption in their partner plants. In addition, fungi also play a role in slowing the decomposition of decaying organisms, which keeps carbon locked in the soil and out of the atmosphere (*See the Boston University and Forbes Articles for more detail on these concepts).*

7. ***Fungi are threatened by human development.*** Without proper protection measures, several species of fungi are at risk due to human activities. Nitrogen pollution, whether from fertilizers or from fossil fuel emissions, tends to infiltrate the soil and have a deadly effect on the fungi that live in it. If fungi thereby became driven from ecosystems, these ecosystems would lose a life form that cools its surroundings and helps regulate atmospheric carbon levels. This could trigger a chain reaction that threatens both the climate and other species that depend on fungi for survival. Even though fungi are arguably not studied by conservationists as much as plants or animals, it will be important in the coming years to maintain surveillance of their population sizes and take appropriate

measures to ensure they do not become endangered (*See the Boston University and Forbes Articles for more detail on these concepts).*

Relevance for Sustainable Development Goals and Grand Challenges
(https://sdgs.un.org/2030agenda)

The fungal role in the ecosystem relates to several SDGs, including

- **Goal 7. Ensure access to affordable, reliable, sustainable, and modern energy.** The mechanisms by which fungi cool their surroundings could be further studied and exploited to cool households with less electricity. The high water content of fungi and their high capacity for transpiration allows an interesting avenue for potentially reducing energy consumption.
- **Goal 13. Take urgent action to combat climate change and its impacts.** Through their role in supporting plants, cooling their environments, and helping to trap carbon in the soil, fungi play a vital role in reducing carbon emissions and fighting climate change. Without the fungi, climate change would likely accelerate
- **Goal 15, Protect, restore, and promote sustainable use of terrestrial ecosystems.** Fungi and the ecosystems they live in are currently under threat due to pollution and development. Nitrogen pollution from fossil fuels and from fertilizer runoff has harmful effects on fungal species. In addition, unique fungal species can be lost when ecosystems are developed for human activity and infrastructure. It is important to continue to monitor how fungi respond to human activities and to place protection measures that will ensure their survival.

Potential Implications for Decisions

1. ***Individual***
    a. Weigh up the beneficial role of fungi, both in the ecosystem and in our everyday lives.
    b. Do larger fungi automatically produce more cooling power?
    c. How large is the potential of fungi to cool a box? A room? The planet?

2. ***Community Policies***
    a. Local environmental consequences
        i. How does the loss of fungi impact an ecosystem?
        ii. How does the development of green space impact fungi?
        iii. How does the use of certain herbicides impact fungi?
    b. Maintenance of local greenbelts and parks
        i. Why are parks and green spaces important for fungi?

3. ***National Policies***
    a. Fighting Climate Change
        i. How can the government take steps to combat climate change?
    b. Funding for Sustainable Energy
        i. How can the government increase funding for sustainable energy?

c. When we think of endangered species, we mostly think of plants or animals? Should certain fungi be considered endangered species?

d. How can national parks protect fungi? How can we protect fungi when we visit national parks?

Pupil Participation

1. ***Class discussion of the implications – personal, societal, global – of fungal sweating***

2. ***Pupil Stakeholder Awareness***

a. Where can you find good fungi in your home? (Sample Answers: Yeast, Bread, Mushrooms, Blue Cheese, Miso Paste, Soy Sauce, Kimchi)

b. Do you know of or have you noticed any wild fungi in and around your community? Is it a yeast, mold, mushroom? Can you identify its genus or species? Free phone apps (e.g. iNaturalist.org) may be useful for identifying the genus and species of some fungi.

c. What can you do to make sure wild fungi have a place to grow?

3. ***Exercises***

a. Of all the hypotheses for why fungi are colder than their environments, what do you think is the most supported? Why?

b. *If possible to do safely* and under adult supervision, go on a hike or nature walk; have students touch (but not grab or taste) wild mushrooms and make observations about the mushroom's temperature in relation to the surrounding temperature. This nature walk would be especially insightful two days after it rains, especially during the spring or fall.

c. Conduct an experiment to create a mushroom-powered air-conditioner using whole portobello (*Agaricus*) mushrooms available in groceries (see Appendix).

d. A report of the observations, discussions, and/or findings generated by the teachers and students may be published in the comments sections linked to the biorxiv publication by Cordero et al. 2020.

The Evidence Base, Further Reading, and Teaching Aids

Younger Grades (Ages 6-12) (highly recommended)
Sciencing Evaporative Cooling
Kids' Health- Why We Sweat
Ducksters- Fungi
SciShow Kids Fungi Video
TEDED-Why We Sweat

Older Grades (Ages 12-18)
YouTube Video: Blackbody Radiation
YouTube Video: *Amanita muscaria*
San Francisco Chronicle: How House Plants Save Energy

Boston University Fungi Climate Warriors
Time Article Fungi Fighting Climate Change

Class Activities
Easy Fermenter Starter Kit

Advanced Reading

Fungi are Cooler than Their Surroundings
Evaporative Cooling of Mushrooms

Glossary

Buller's Drop: a small drop of water that condenses onto a mushroom's surface to aid in spore release.
The Carbon Cycle: the cycle that explains how carbon is transferred between plants, animals, other organisms, and the atmosphere.
Condensation: the action of water turning from a gas to a liquid. A similar process happens in clouds during the water cycle.
Convection Currents: currents created by the rising of warm air and the sinking of cooler air.
Endangered: used to describe a species that is at risk of becoming extinct.
Evaporative Cooling: the process where a liquid turns into a gas and absorbs energy from the surroundings. Used to keep humans, plants, and fungi cold.
Fungi: a kingdom of life including molds, mushrooms, and yeasts.
Gills: thin structures that are found under a mushroom cap. They greatly increase surface area and aid in the rates of evaporative cooling.
Hypothesis: an educated guess that scientists make for the outcome of an experiment.
Infrared Radiation: a type of radiation invisible to the eye and detected by the skin as heat.
Microbolometer: a device used to detect infrared radiation in thermal cameras.
Microscopic: unable to be seen by the naked eye.
Mushrooms: the fruits of fungal mycelia.
Mycelia: the main growing structure of a fungus.
Mycorrhizae: a fungus that benefits a plant species in return for receiving benefits from a plant species. A fungus that is in a mutual symbiotic relationship with a plant.
Perspiration: another word for human sweat.
Sporulation: the act of producing spores.
Stefan-Boltzman Law of Radiation: a law (or fact) that relates radiant energy with temperature.
Surface Area: a measure of the total area an object occupies.
Thermal Images: images that display different temperatures rather than different colors.
Thermocouple: a device that uses the relationship between electricity and heat to measure the temperature difference between two different points upon physical contact.
Transpiration: usually used when referring to plants giving off water.

Acknowledgements

All diagrams were created with Biorender.com.