Microbes help plants tolerate drought

Mommy, why is there so little grass on the football field these days?

Photo by Jesús Mercado Blanco (CSIC).

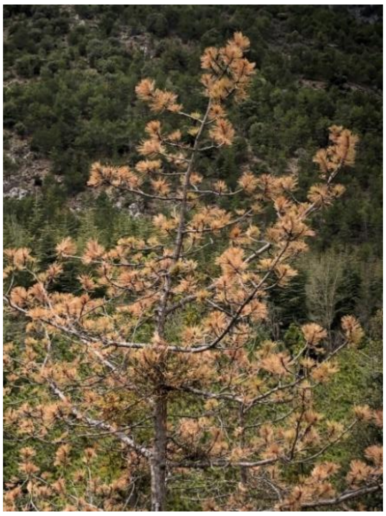

Photo by Manuel Fernández López (CSIC).

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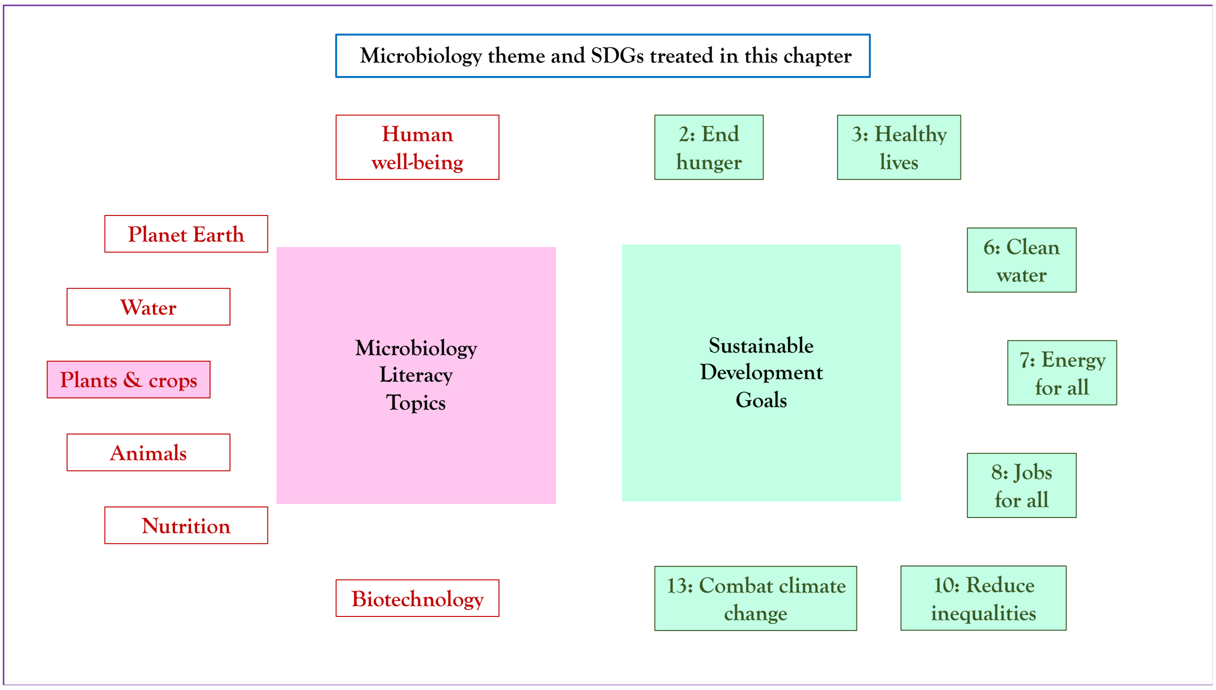
Microbes help plants resist drought

Storyline

Global warming and climate change are increasing both the severity and duration of drought, and converting healthy productive soils into arid lands where plants can only grow slowly and poorly. However, all is not lost: microorganisms dwelling in the plant ecosystem can help plants stay green longer and better tolerate extreme weather conditions such as severe and intense droughts. The size of drought footprints can thus be reduced by improving water management, and protecting our plants and the ecosystem where they develop, including their microbes.

The Microbiology and Societal Context

The microbiology: plant microbiome/plant:microbe interactions; drought/water stress tolerance; nutrient acquisition; plant microbial biotechnology. *Sustainability issues:* plant crop production and food security; use of arid land/extension of farmland; hunger; health; energy; economy and employment; global warming, climate change and desertification.



Microbes help plants resist drought: the Microbiology

1. ***Climate change and the problem of droughts.*** Climate change refers to a change in the typical weather of a region over a long period of time, commonly characterised by variations in temperatures and rainfall levels. Overall, Earth is getting warmer and drier. Higher temperatures lead to unusual weather patterns, including frequent and severe droughts. Extreme events such as droughts lead to water shortages that have strong impacts on many aspects of our lives.

Not having enough water jeopardizes the ability of plants and animals to grow, and may even compromise their survival! Drought poses a great threat to all kind of plants: from agricultural ones to ancient forests, from garden plants to species for recreation.

Did you know that if there is a water shortage, we might not be able to irrigate football pitches, tennis courts or golf courses, so we might no longer be able to play with our friends or watch our favorite competitions?

What is more, if plants can't grow, the animals and people who feed on them will also have serious problems to survive; for instance, we will not have enough boxes of breakfast cereals (made of wheat or corn). Not to mention that, if the streams, rivers, lakes and water reservoirs fall, our drinking water supplies diminish!

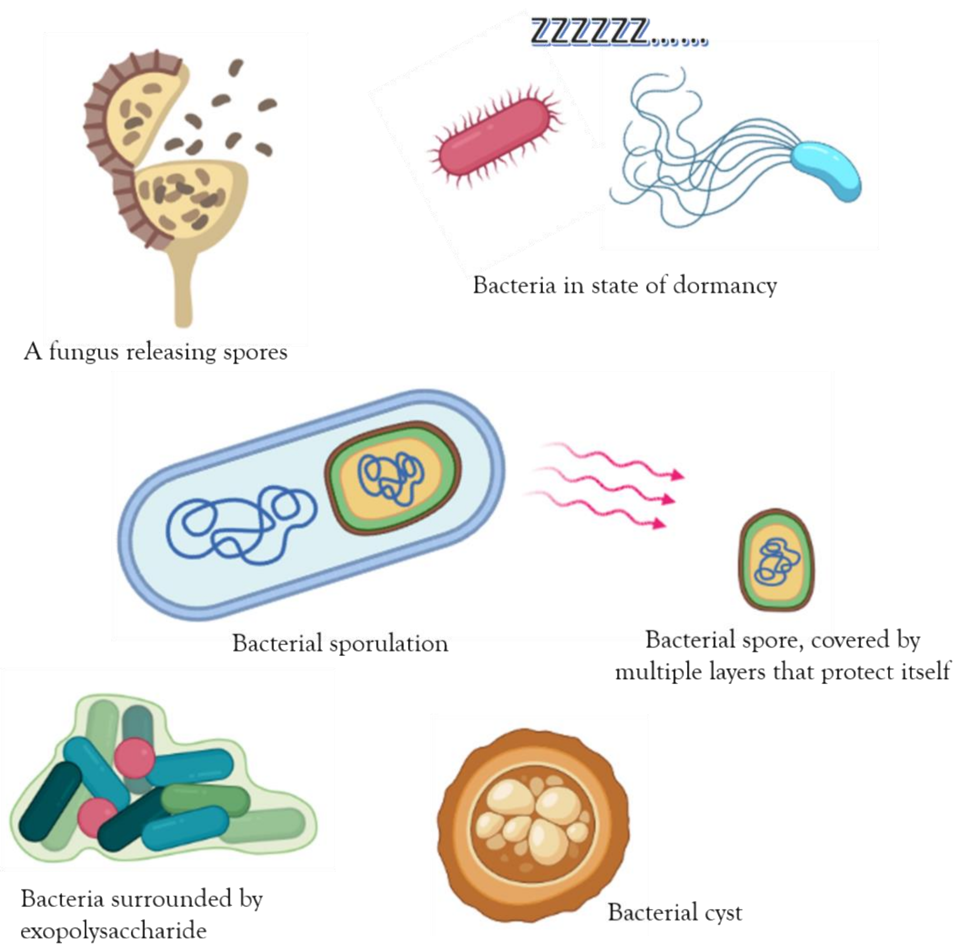
2. ***Long lasting droughts lead to the formation of arid (dry) lands.*** Currently, the Earth's surface consists of 71% of water and 29% of land; 33% of the total land area is classified as desert, and this is increasing in size.

Repeated droughts create arid soils due to the water deficiency itself and to the consequent low vegetation coverage in these areas. Many dry lands have very low levels of nitrogen and organic matter, and high salinity levels. The accumulation of salt in soils has drastic consequences for plants, for example high toxicity and imbalances in terms of plant nutrition. Do you know that around 50% of the global arable lands are estimated to be salinized by 2050? In addition, soil aridity reduces microbial diversity and functional potential, limiting their capacity to support plant health. As a result, the extent of crop and forestry areas will reduce.

3. ***Desiccation is not a problem for some microorganisms[1], since they have developed different mechanisms to tolerate water deficiency.*** As we do not feel like having fun, working or going to the school when we are very hot or thirsty, neither do microorganisms, so they "go to bed" during water shortage. In this case, we say that microorganisms enter in a state of dormancy, during which their activity slows down reversibly. Other microorganisms such as some bacteria and fungi can produce spores or microscopic structures super-resistant to drought, a type of armor. Bacteria can also produce exopolysaccharide, a coating layer that protects them and the surrounding ecosystem from the harsh environmental conditions. Thanks to these strategies, microbes can remain protected even during long periods of drought without being affected.

[1] The terms *microorganisms* and *microbes* refer to bacteria, archaea, fungi, yeasts, virus, protists, etc.

Box 1: Microbial strategies to resist water deficiency



4. ***Plants harbor a wide diversity of microorganisms which are essential for their survival: the plant microbiome.*** Plants are sessile, that is, they cannot move around like we can. Thus, they are not able to pick up their roots and move to a wet area when they face a severe drought. For that reason, they have developed their own mechanisms to deal with these extreme conditions.

In addition, and most importantly, microorganisms play a key role in defending plants from various biotic and abiotic stresses (those caused by other living organisms or by unfavorable environmental conditions, respectively).

Many people view microbes as being harmful to humans, animals or plants, and some even think that microbes should be eliminated from the environment. However, while some do cause plant diseases, the vast majority are either harmless or beneficial.

A wide diversity of different microorganisms dwell on and in most of the plant tissues without causing any damage: they can be found on plant surfaces (epiphytic) even inside (endophytic) the roots, trunks, leaves, flowers, etc. These microbes are termed the microbiome – all the microbes associated with the plant – and as we will see below, they are essential for plant growth and survival. And while some members of the microbiome can vary from plant-to-plant, and over time, others form stable mutually-beneficial – symbiotic – relationships with the host plant.

5. ***Microorganisms increase plant tolerance of water deficits.***

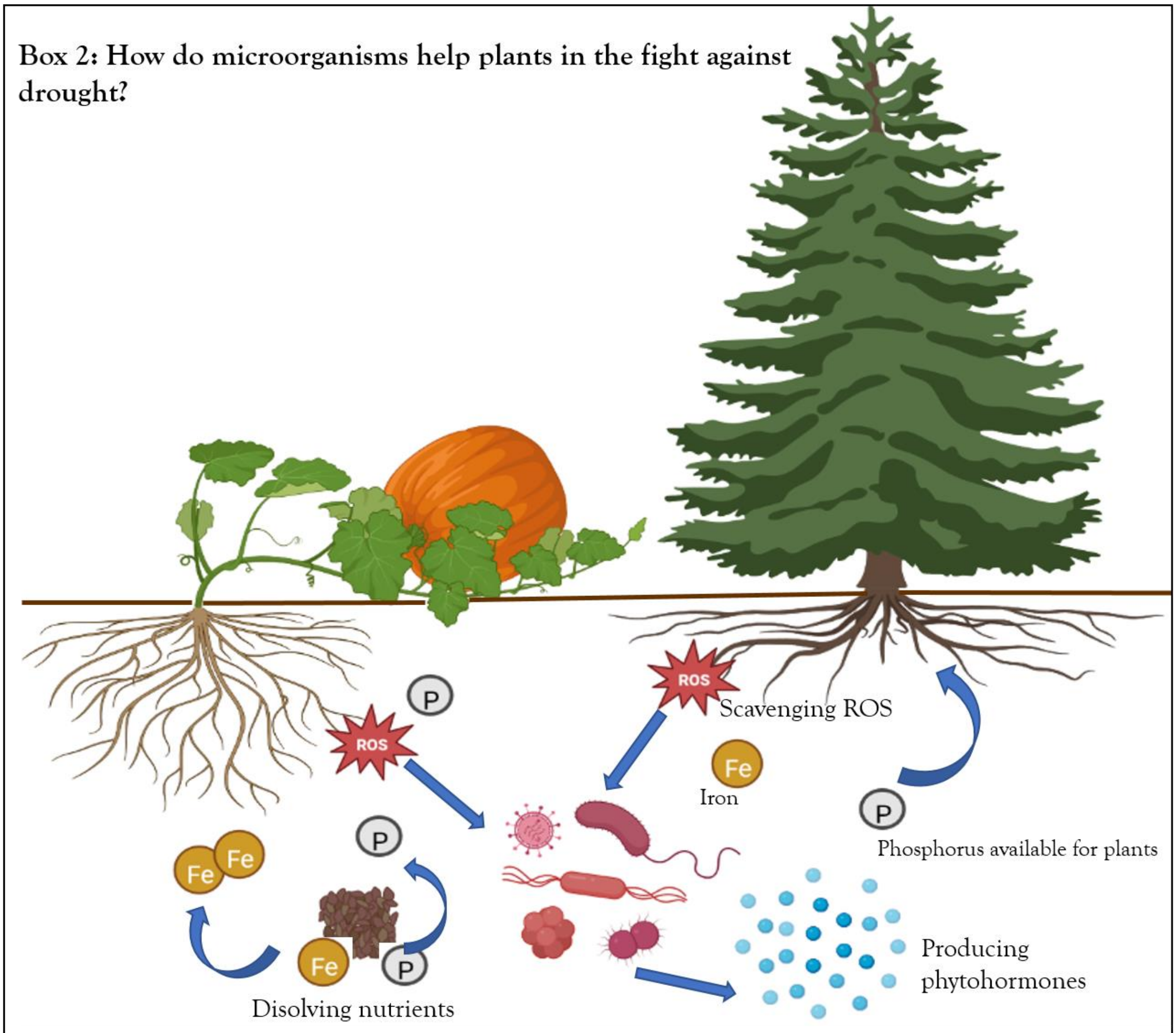
a. Nutrient uptake. During water shortages, the ability of plants to acquire nutrients from the soil is reduced. This is because nutrients in or on soil particles need to dissolve in water in order to move in the soil and reach the plant roots. If there is less water available, they dissolve less and so remain unavailable on the soil particles.

But microbes can improve the nutrient availability and uptake by the plants, by growing on the soil particles, dissolving the nutrients and transferring them to the plants. Imagine a pantry where the food is placed high up, and you need a ladder to get to it: microorganisms act as that ladder for the plants.

b. Root growth. Some microorganisms produce compounds named phytohormones (=plant hormones) which are necessary for plant growth and drought stress alleviation. These phytohormones stimulate plants to develop more roots such that the surface area for water and nutrient absorption increases.

c. Stress protection. Drought stress also induces in the plant production of Reactive Oxygen Species (ROS), compounds that damage proteins and other molecules responsible for metabolism in plant cells, and can lead to cell death. Microorganisms can scavenge ROS and reduce their levels in the plants, protecting them from the harmful effect of the water shortage.

Box 2: How do microorganisms help plants in the fight against drought?



6. ***Microorganisms are a natural and eco-friendly tool in mitigating water deficit stress in plants.*** Since beneficial microbes inhabit healthy plants and protect them from drought stress, we can exploit them to mitigate water deficit stress in many plant species. We do this by adding them to plants as natural fertilizers, using them as sustainable tools to increase tolerance to various stresses, including drought. For example, adding microbes tolerant to high salt concentrations to crop plants enables them to be planted in arid regions, and hence the transformation of a desert-like area into arable land. In this way, it is expected that the use of microorganisms as fertilizers will lead to an expansion of agricultural areas.

Cucumber plants grown under drought conditions treated (left) or not (right) with protective bacteria. Photo by Wang C-J and colleagues (https://doi.org/10.1371/journal.pone.0052565)

Relevance for Sustainable Development Goals (SDG) and Grand Challenges

- **Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture**. As a result of global warming, severe and frequent droughts are increasing the area of arid land and desert on the planet, in which most agricultural crop plants grow with difficulty or not at all. Water shortages in productive farmland will entrain another type of shortage: food scarcity. In this sense, the use of microbes as fertilizers helps in achieving this SDG since, thanks to microorganisms and their positive interactions with plants, the agricultural resources will not be so severely compromised.
- **Goal 3. Ensure healthy lives and promote well-being for all at all ages.** Food is essential to survival, and food quality is an important determinant of good health. Although some plants can survive and grow in drought conditions, the nutritional value of their seeds or fruits is significantly lower than those produced by plants grown under optimal conditions. However, when microorganisms are applied as fertilizers to plants grown under low water conditions, they can provide essential nutrients that make their fruits more complete in terms of nutritional composition. Microorganisms can therefore not only ensure the availability of agricultural resources but can also improve the quality of our food, and hence our health (and that of our farm animals fed on agricultural crops). In addition, the use of microorganisms to increase the tolerance of plants to drought contributes to the maintenance of forests, football pitches, tennis courts and golf courses that are important for recreation, and so contributes to physical and mental wellbeing.

- **Goal 6. Ensure availability and sustainable management of water and sanitation for all**. The use of microorganisms to recover dry or desert areas contributes to the achievement of this SDG, since with their help the soil and water toxicity can be reduced. In addition, microbe-based fertilizers could replace chemical fertilizers and therefore, diminish the associated water pollution of chemicals. However, the large-scale production of microorganisms is a high water-consuming process, and needs an additional step of water sanitation.
- **Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all.** By using plant microorganisms as fertilizers, dry and desert areas could be used not only for agricultural purposes but also for growing bioenergy crops. However, the large-scale production of microbe-based fertilizers is an energy-intensive process.
- **Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.** The industry of fertilizers based on beneficial microorganisms involves different businesses, such as research, production, marketing, transportation and sale of the fertilizers, etc, so many different jobs could be created. In addition, dry lands could be optimized for agricultural or forestry exploitation, which in turn could involve more employment opportunities.
- **Goal 10. Reduce inequalities.** Desertification – extension of arid areas – is a great concern worldwide, especially in impoverished regions of the planet. Turning such dry areas into farmlands with the help of microorganisms will reduce income inequalities in some countries which could export their plants, plant products and even the animals that feed on the growing plants.
- **Goal 13. Take urgent action to combat climate change and its impacts.** The use of microbial fertilizers for plants reduces the need for chemical fertilizers, the production of some of which is energy intensive and hence associated with large carbon footprints. In addition, the recovery of dry lands with new healthy plants results in an increase in the rate of photosynthesis in these areas, and the associated drawdown of carbon dioxide, a major greenhouse gas fuelling global warming and climate change. Moreover, the use of microorganisms to create healthy forests will provide many beneficial effects for the environment: trees and forests are the "homes" of diverse and unique animal, plant and microbial species, and are crucial to their survival and hence to biodiversity, regulate climatic and important hydrological processes, and are a major source of important products used by humans (wood, fuels, medicines, etc.).

Pupil Participation

1. Class discussion of global warming, climate change and its effects on plant growth, and the potential of microbes to counteract these effects.

2. Pupil stakeholder awareness

a. Concerning the use of microbial inoculants to increase plant tolerance of stresses

i. Why should we care about the process of desertification?

ii. Should we inoculate plants with microorganisms that do not inhabit the plant species we want to protect? From which ecosystems should we obtain the microorganisms to be inoculated?

iii. Do we run the risk of transferring pathogenic microorganisms to the plants at the time of inoculating them?

iv. Should the microbes be genetically modified to make them more effective?

v. Does the inoculation cause ecological damage?

vi. How much water is employed to obtain the microbial fertilizer?

b. What can I personally do to reduce global warming?

c. What can I personally do to conserve precious water, so that there is more for the plants?

3. Exercises

a. Find maps – current and historical – of the world showing arid lands. Calculate the proportion of total landmass that arid lands represent. Draw a graph showing how these proportions have changed over the years for which you have maps.

b. Which are the regions of the world most affected by the changes?

c. Where do you think the application of microbes to increase plant tolerance of drought might be most effective? Why?

Further Reading and Teaching Aids

Climate change: https://climatekids.nasa.gov/kids-guide-to-climate-change/
Problems faced by plants in dry conditions and mechanisms to protect themselves: https://kids.frontiersin.org/articles/10.3389/frym.2017.00058
How microbes protect plants against the droughts: https://www.washington.edu/news/2016/09/19/microbes-help-plants-survive-in-severe-drought/

Glossary

Abiotic stress: a type of stress or harmful condition, that is caused by non-biotic factor(s) such as those of environmental origin. For instance, as a consequence of extremely high or low temperatures, drought, floods, high solar radiation, intense winds, etc.
Biotic stress: a type of stress that is caused by living organisms such as microorganisms (usually pathogens), animals, humans, etc.
Climate change: long-term changes in climate patterns, commonly characterised by the increase in temperatures and drastic shifts in rainfall levels. These changes could take place at regional or global scale, and they are usually of human origin.
Dormancy: a physiological state in which bacteria remain quiet, keeping their metabolism rates to a minimum. This state tends to begin when bacterial cells face a stressful condition and needs to be protected, for instance, in case of nutrient depletion.
Endophytic microorganisms: those microorganisms that inhabit inside the plant tissues. They can be found inside the plant cells or between them. These types of microorganisms are thought to play essential roles in plant development.
Epiphytic microorganisms: those microorganisms that inhabit over plant tissues. For instance, over the roots (rhizospheric microorganisms), the leaves (phyllosphere microorganisms), the flowers, etc.
Exopolysaccharide: an organic compound, produced by bacteria and some fungi, that plays essential biological roles. It mediates microbial adhesion to different surfaces, confers

environmental protection to the producer cells, for instance, against other microorganisms. Tartar on teeth is made of bacterial exopolysaccharide.
Phytohormone: (or plant hormone). Organic molecules with a strong influence on plants' physiological processes; they coordinate cellular activities on plants (plant growth, flowering, leaf senescence, root development, etc). Phytohormones are produced by plants but also by microorganisms.
Reactive Oxygen Species (ROS): unstable molecules that contain oxygen and interact with organic molecules in a plant or human cells. They cause damage to DNA, RNA, proteins, even cause cell death.
Sessile: an organism that is permanently attached to one place and cannot move around.
Spore: a rounded resistant form adopted by bacterial cells in adverse conditions.
Symbiosis: a type of relationship between different organisms, usually belonging to different species. It is characterised by the mutual benefit of both organisms.

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