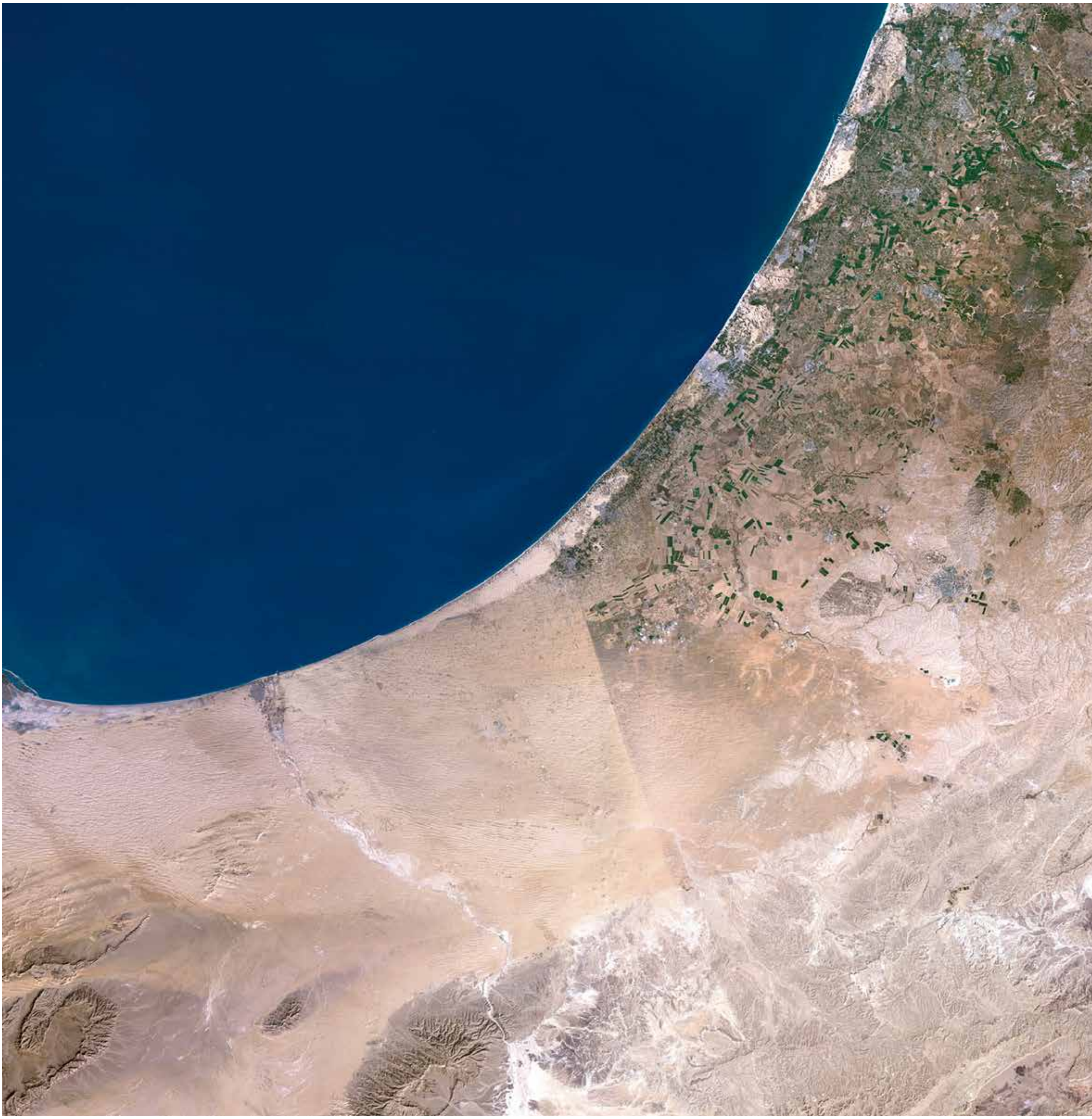


Border region between Egypt (left) and Gaza and Israel (right). The difference in the shades of the terrain in the uncultivated areas reflects changes in the desert soil on the Egyptian side. This makes this border one of the few that can be seen from space.

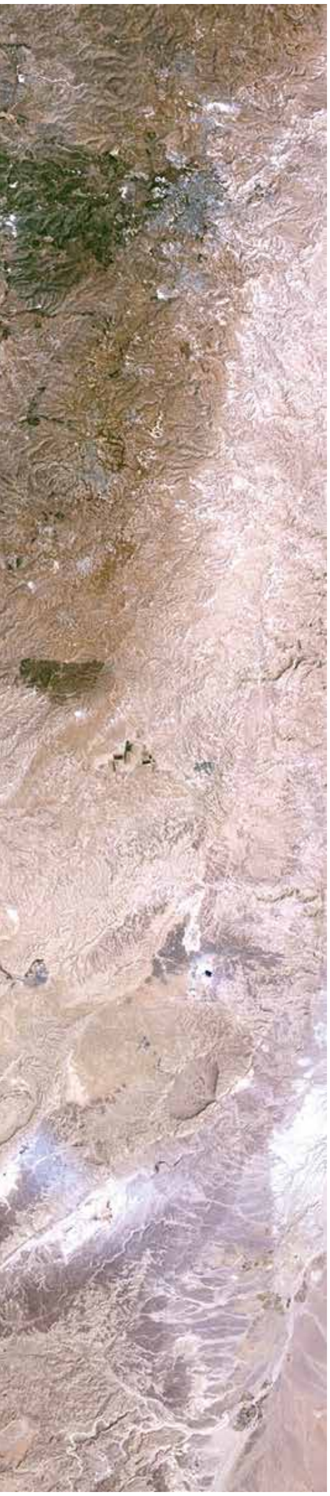


PHOTO: SCIENCE PHOTO LIBRARY/PLANETOBSERVER

ALGAL BLOOM IN THE DESERT SAND

TEXT: KLAUS WILHELM

Drought, heat, and glaring sun. A desert habitat is one of punishing extremes. If a plant is to survive here, it must be able to endure a lot. This is especially true for algae. Together with Mark Stitt and his team at the Max Planck Institute of Molecular Plant Physiology in Golm near Potsdam, Haim Treves is investigating how the alga *Chlorella ohadii* has adapted to the extreme living conditions of the desert.

> **“At first, we thought our measuring devices were malfunctioning. But it wasn’t the instruments – it was the algae.”**
>
> *HAIM TREVES*

Chlorella ohadii is a unicellular green alga that is named after the man who discovered it, the eminent biochemist and photosynthesis researcher, Itzhak Ohad. He was Treves’ long-time mentor and friend, who died in 2016. Ohad was the first to isolate and study this organism, and his research made a major contribution to our fundamental understanding of photosynthesis. It has now been 10 years since Haim Treves was a PhD student at the Hebrew University in Jerusalem, where he regularly explored the desert. The young scientist brought back samples from his excursions to the Israeli Negev Desert of the wafer-thin sand crust that covers the desert’s floor. “This crust has the consistency of cornflakes in the areas of the Negev that are farther away from the coast. It breaks with a soft crackle when you step on it. But along the coast, where the air is more humid, it feels more like you’re stepping on a sponge,” describes Treves.

The crust appears completely lifeless. But in fact, it harbors a unique community of microorganisms. For example, cyanobacteria – bacteria formerly known as “blue-green algae”, many of which perform photosynthesis and get their energy from sunlight. Treves and his colleagues wanted to isolate these bacteria from the sand crust and grow them in the laboratory. But tiny green specks would always appear in their cell cultures after a short time. “At first, we thought we had been careless and contaminated our samples,” he recounts. But they just couldn’t get rid of the green specks. Itzhak Ohad finally persuaded Treves to look into the mystery. Treves identified the green specks as colonies of the green algae *Chlorella ohadii*. “I really owe him a

Cyanobacteria of the genus *Leptolyngbya* form unbranched chains. They are found in a wide variety of habitats, e.g. in thermal springs, in Antarctica, as well as in deserts. In the Negev Desert, the cyanobacteria live in the crust that covers the ground.

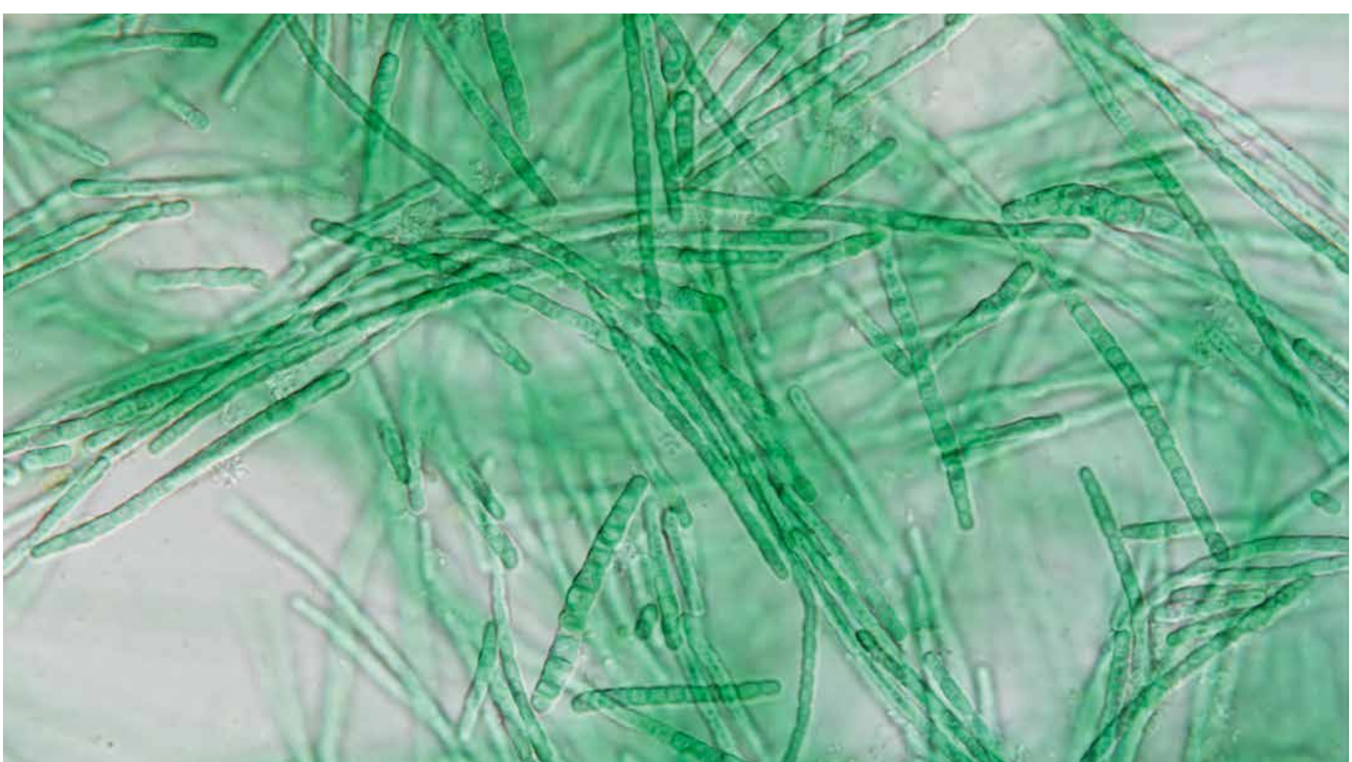
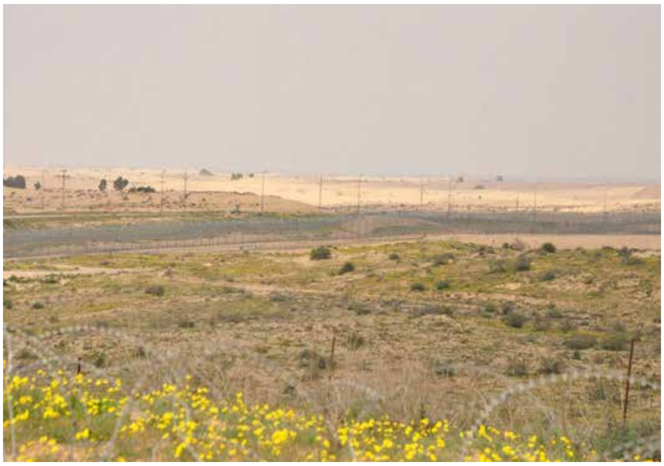
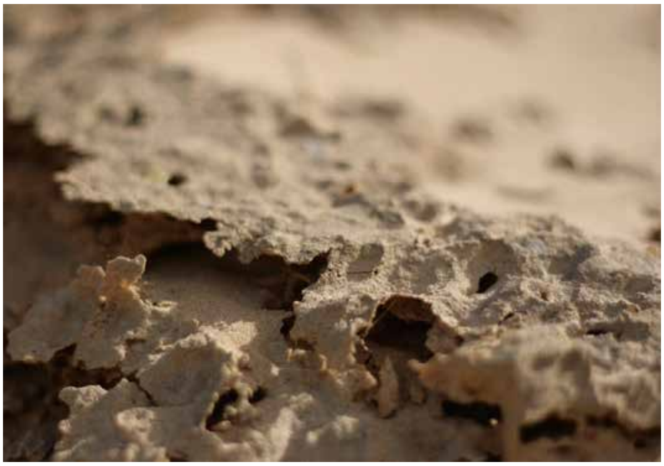


PHOTO: CCALA

PHOTOS: HAIM TREVES/MPI OF MOLECULAR PLANT PHYSIOLOGY



Border between Israel (foreground) and Egypt. In spring, flowers bloom on the Israeli side of the Negev Desert, while the Egyptian side, in contrast, is largely devoid of vegetation and is covered in sand – this is a result of the destruction of the soil crust by vehicles and overgrazing.



A layer about two millimeters thick covers the desert surface. Over many decades, microorganisms have produced carbohydrates that have combined with the sand and baked into a brittle crust resembling cornflakes. This crust stores water better than pure sand and it protects the ground from erosion and complete desiccation.

special debt of gratitude for his guidance and inspiration, and it makes me very happy that his legacy lives on in the name of this alga." Treves quickly recognized the alga's extraordinary abilities: not only did *Chlorella ohadii* defy extreme exposure to sunlight – the more light the researchers shone on it, the faster it grew. Even at four times the light intensity of the desert, the algae continued to flourish. "We thought it was our fault and that our meters were defective," says Treves. However, this phenomenon was not due to the instruments, but rather to *Chlorella ohadii* itself: not only does it survives in one of the most extreme habitats on Earth – it is also one of the fastest growing organisms ever discovered. Mark Stitt was also fascinated by the discovery. The former Director at the Max Planck Institute of Molecular Plant Physiology uses cutting-edge technology to research photosynthesis. Like most of his colleagues, he uses model organisms such as *Arabidopsis thaliana*, spinach, potatoes, and tomatoes because the genetic material of these plants has been decoded, and many of their metabolic pathways are known. "But sometimes it's a good idea to leave familiar territory. If we are focusing on only a few species, it is easy to overlook how differently plants can adapt to their environment. And it's under extreme conditions that plants can develop completely unexpected capabilities," says Stitt. So it was only logical that Treves should go to the Max Planck Institute in Golm after he got his doctorate, so he could conduct further research on *Chlorella ohadii*.

SUMMARY

The green algae *Chlorella ohadii* defies extreme drought and solar radiation in the soil of the Negev Desert. It employs various adaptations to protect its photosynthetic mechanisms against the glaring sunlight. A crust only few millimeters thick on the soil surface protects it from drying out. Bacteria form a gel-like layer by excreting carbohydrates, which can store water better than sand.

Researchers want to transfer this alga's properties to crops to enable them to photosynthesize effectively – even at high levels of solar radiation.

The life of this alga is characterized by extremes: during the day, it is not uncommon for temperatures to rise to up to 60°C; the sun and heat completely dry out the soil. At night, on the other hand, temperatures can plummet so far that frost can form. At dawn, the little moisture that there is in the air settles as dew on the ground. The proper amount of water and light that *Chlorella* needs to exist is available only in the brief period just after sunrise, before there is once again too little of one and too much of the other.

Particularly the photosynthesis of this alga is optimally adapted to such conditions. Electrons play an important role in converting solar energy into chemical energy. For every photon that is absorbed by the chlorophyll molecules, one electron is elevated into a higher energy state. These energized electrons provide the energy to 'split water' and turn it into oxygen and hydrogen atoms. However, the sun's rays are too strong in the desert. "Then the photosynthetic machinery gets overloaded and melts down – like a short circuit," explains Stitt. High light intensity can also produce "singlet oxygen" – a highly reactive form of oxygen that damages the photosynthetic apparatus.

Beyond a certain point, increased solar radiation no longer leads to a higher photosynthetic output. Instead, it stagnates and even decreases with increasing radiation. Dryness intensifies this effect, because it hampers the

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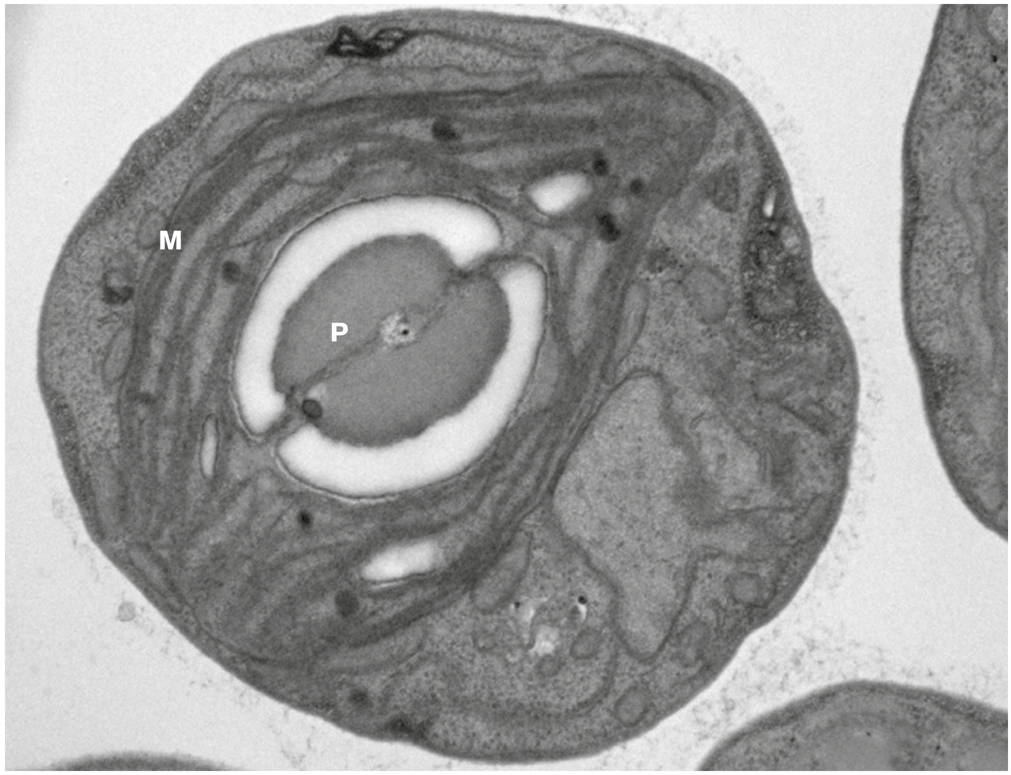

An electron microscope reveals the details of the photosynthesis mechanisms of *Chlorella ohadii*. The chloroplast occupies a large part of the cell. Its stacked membranes (M) make photosynthesis particularly effective. The pyrenoid (P) serves the same purpose. It is enriched with the carbon dioxide needed for photosynthesis as well as a key enzyme. The pyrenoid is surrounded by a layer of starch (light ring).

PHOTO: HAIM TREVES/MPI OF MOLECULAR PLANT PHYSIOLOGY

use of the light energy to drive carbon dioxide fixation and other metabolic reactions. The researchers found that *Chlorella ohadii* has evolved several mechanisms – some unique – as protection against such short-circuits. They allow the alga to quickly establish a balance between oxidation and reduction reactions. Without this balance, too many electrons would accumulate. "Like a car that shifts into a lower gear when going down a steep hill, this alga prevents damage to the photosynthetic system," says Haim Treves. Furthermore, the electrons flow within a closed circuit during photosynthesis in *Chlorella*, because only a circulatory system can prevent a surplus of energy-rich electrons under the desert's extreme conditions. Otherwise, the electrons would be stuck like cars in a traffic jam, with some even flowing backwards. *Chlorella* also produces enzymes that neutralize destructive singlet oxygen molecules.

Studies by the Max Planck researchers also revealed that *Chlorella* can effectively photosynthesize even in low light. The alga employs the very same 'tricks' when it grows in low light that it uses to cope with very high light intensities. When solar radiation increases, *Chlorella* can quickly raise its photosynthetic output and produce 60 times more starch than under low levels of light. "The growth rate of the algae increases within minutes – it's like a turbocharger gets turned on," says Treves.

But all these adaptations would not be enough if there were not another very special habitat in the Negev Desert that, together with bacteria and fungi, enables the algae to survive under the most adverse conditions: the two-millimeter-thick crust on the desert floor. It is

"Plants often develop unexpected abilities, especially under extreme conditions."

MARK STITT

formed when the pioneers of the desert – the cyanobacteria – settle on the surface of the sand layer. Over many years, they produce large amounts of carbohydrates, which form a gel-like mass. This mixes with the sand grains and creates a crust when it dries. The gel can better retain the moisture when water in the form of dew or – very rarely – rain wets the soil. It also dries out more slowly than pure sand. This allows the crust to provide more water for the microorganisms living within it. Only when over half of the stored water has evaporated over the course of the day do the microbes temporarily cease their activity. In laboratory experiments, Treves was able to demonstrate that the crust actually prevents its community of microbes from drying out: together, cyanobacteria and *Chlorella* survive the aridity typical of the desert – on their own, the algae would die. Researchers have even found evidence that this crust-dwelling organisms prepare for daily desiccation: before sunrise, the cells produce substances that will help them revive from their dry state the following night.

Tiny tubes in the crust

Treves's mentor Itzhak Ohad and his colleagues have observed other fascinating phenomena under the microscope. The cyanobacteria can form vertical tubes in which they can migrate towards the light. "When we put a piece of crust in a Petri dish in the lab and spray water on it, the bacteria come to the surface and form a green layer upon it. Other times, the crust seems to turn black, because the bacteria are shielding themselves with endogenous sun protection factors," says Treves. *Chlorella* and the other microorganisms in the crust also benefit from this light protection. Thus, without the cyanobacteria, the algae could not survive.

ADAPTATIONS TO LIFE IN THE DESERT

ROOTING
Formation of deep or extensive roots

SAVE WATER
Impermeable surface (e.g., a layer of wax)

Closed stomata during the day
Fewer or smaller stomata

Smaller or no leaves

Hair as protection against light and evaporation

SUN PROTECTION
C4-photosynthesis: Nocturnal CO_2 fixation in the form of malate and the conversion to carbohydrates during the day

Production of sun protection factors, like aloe

Minimizing the area exposed to the sun by turning away from the light

DISTRIBUTION
"Dormant" seeds that take years to germinate in drought conditions

Explosive growth of seedlings in the presence of moisture

In general, bacteria seem to be the secret rulers of this ecosystem. If resources become exceptionally scarce, the bacteria can even bring the growth of the algae completely to a halt.

The importance of the ecological function this soil crust performs is visible along the Israeli-Egyptian border. Tire tracks and other signs of human activity dominate the Egyptian side. Because the crust is largely destroyed, a sandy desert has spread out on this side of the border. The Israeli Negev on the other side is a restricted military area and may not be entered by unauthorized personnel. So there the crust is still largely intact. The significance of this becomes evident after rare rainshowers in the desert: the Egyptian Negev remains brown, but the Israeli Negev blossoms and briefly transforms into a sea of flowers. "The crust prevents the sand from spreading. So plants can thrive there after it rains," explains Treves.

The Chinese government has recognized the crust's stabilizing on sand dunes and soil fertility. In an experiment, Chinese researchers have inoculated sand dunes of the Hopq Desert with cyanobacteria and artificially irrigated them. They're hoping a sand crust and ultimately arable soil will be created in this way. It remains to be seen whether such measures will be successful. Treves takes a different approach to helping crops grow better in arid and semi-arid regions. In his opinion, *Chlorella ohadii* itself is the key: "If we understand what makes it so resistant to drought and high levels of sunlight and how it can grow so quickly, we can provide other plants with the same capabilities," says Treves. Perhaps this tiny green algae holds one of the keys to sustaining life as global warming continues. It would not be the first time that a presumed measurement error turned out in retrospect to be an important scientific discovery.

www.mpg.de/podcasts/extreme (in German)