The Desertification Crisis

Dad: just look at that dust blowing up from the fields! Will all the soil eventually blow away?

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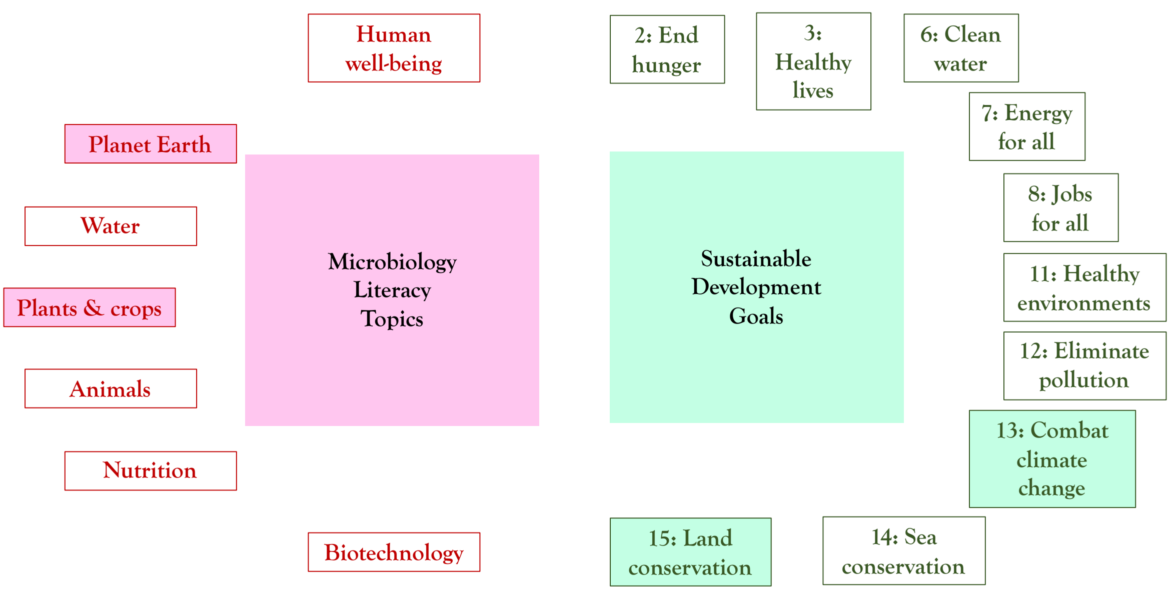
Storyline

Arid lands cover a vast portion (>30%) of Earth and they can end up in very large areas called deserts, the driest places on our planet, either cold (*e.g.*, Antarctica) or hot (*e.g.*, Sahara). Despite their apparent similarities (very dry with little visible life), drylands are actually very different (rocky or sandy / hot or cold/ hyperarid or arid or semiarid). However, almost all deserts are expanding with the ongoing changes in the global climate. This process, known as desertification, degrades soils to a point where they can no longer sustain agriculture, even if the techniques of Desert Farming are implemented. Such processes not only result in the loss of fertility but also enhance soil erosion, leading to the destruction of the delicate habitats of deserts. Such a desert soil crisis also affects other parts of our planet, for instance by generating sand storms which dramatically deteriorate air quality. However, in their natural and undisturbed context, deserts have evolved habitats that limit soil erosion. Two clear examples are the natural formation of microbial mats, in the form of biological soil crusts, and in the rhizosheaths of xerophytic plants. A well-known man-made example is the existance of unique agroecosystems associated with desert oases, where multiple crops coexist in space and time. All these solutions, which have multiple consequences for Sustainable Developmental Goals, are assembled with the irreplaceable and invaluable assistance of microorganisms.

The Microbiology and Societal Context

The microbiology: The soil crisis in arid lands and desertification; microbial mats, biological soil crusts and the microbial exopolymers for sustainability of the desert habitats; xerophytic plants and the rhizosheath biocenosis to enhance biodiversity in arid soils; agriculture in arid lands and Desert Farming. *Sustainability issues*: The oasis and the sustainability of human populations in arid ecosystems and deserts.

Box 1: Microbiology theme and SDGs treated in this chapter

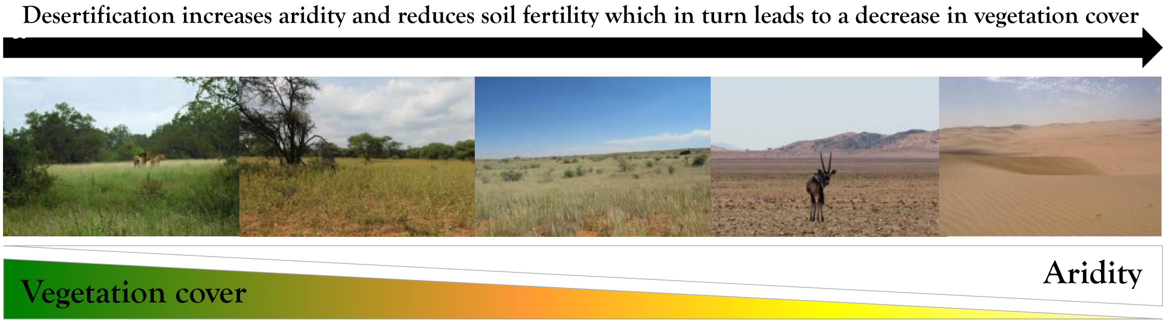


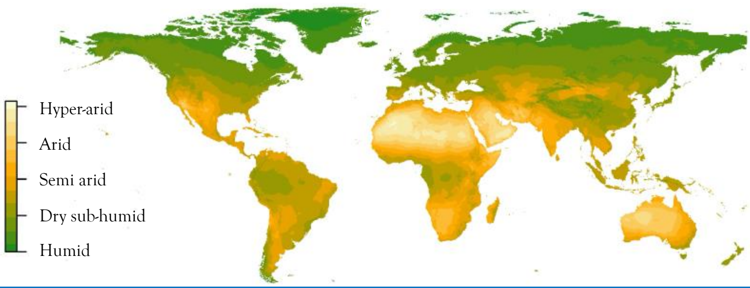
The Desertification Crisis: the Microbiology

1. ***The soil crisis in arid lands and desertification: the role of microorganisms.*** The increasing exploitation of soil for intensive agriculture is accelerating the deterioriation of soil properties, especially of soil structure and fertility, in many regions of the world. Such problems are exacerbated in marginal lands, especially those with limited or unreliable rainfall, where the ongoing effect of climate change is accelerating the processes of desertification. The consequences of desertification, in terms of agricultural productivity, are well understood. A decrease in mean annual rainfall, over a period of years, increases soil aridity with a steady decline in agricultural productivity to a point where, eventually, the land is no longer usable for agriculture. Such above-ground changes represent a food security risk. What we do not know, however, is how desertification affects below-ground factors, particularly those associated with the soil microbiome. Numerous comparative studies of microbiomes in desert soils and non-desert soils have shown us that their compositions are very different. Rather fewer studies have focused on the functions of the below-ground microbiomes, and how they change with increasing soil aridity. As soils become drier, the metabolic processes of soil microbes are reduced, but we still need to understand the size of these changes and, even more importantly, what the broad-scale consequences of these changes are. Plants are sparcely distributed or even absent in drylands leaving soil microbiomes to perform all the so called 'ecosystem services' including important biogeochemical processes, such as carbon sequestration, carbon mineralization, nitrogen fixation, phosphate solubilisation, and much more. As soils become more arid, these processes are likely to be drastically reduced, so the contributions of the soil microorganisms to dryland soil health will also be reduced. Let's consider one specific, and important, example. Carbon sequestration is a key factor in reducing the atmospheric carbon dioxide load (*i.e.*, counteracting the atmospheric concentrations of the major greenhouse gas). Carbon sequestration is a balance between two processes: carbon fixation (gas to solid) and carbon mineralization (solid to gas). We do not yet understand how the delicate balance between these two factors will change with land desertification, and whether the balance will swing in favour of carbon sequestration of carbon dioxide release.

Box 2: Desertification process: from dry sub-humid to hyper-arid environments

Desertification increases aridity and reduces soil fertility which in turn leads to a decrease in vegetation cover



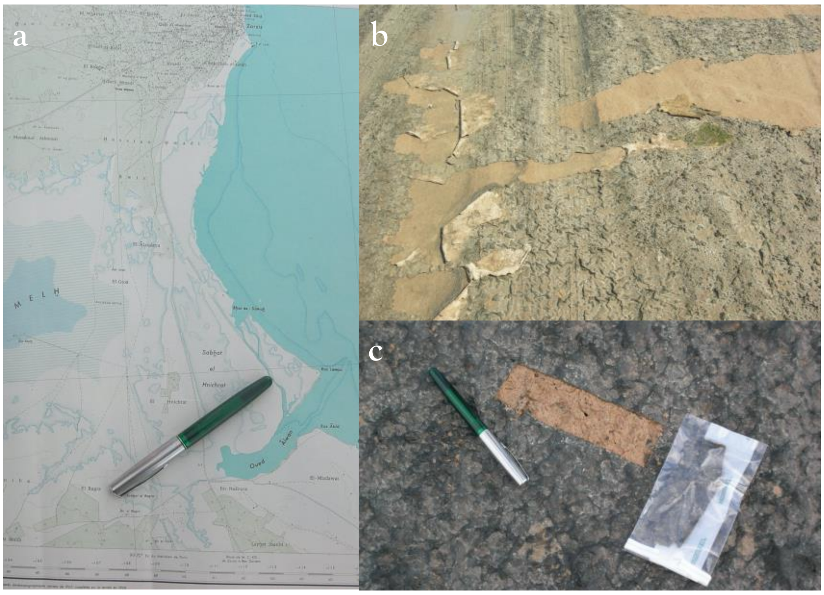


Soil aridity gradient

World map shows the gradient of soil aridity, from hyper-arid to humid areas. Deserts are indicated by yellow to orange colors; these are the environments with little to no vegetation is present.

2. ***Microbial mats, biological soil crusts and the microbial exopolymers for preserving soil structure.*** Fossil records suggest that environmental microorganisms could already form highly structured communities in the form of microbial mats or biocrusts around 2.5 billion years ago, *i.e.*, around two billion years before the appearance of higher plants. The crusts ubiquitously observed at the surface of hot and cold desert soils are named Biological Soil Crusts [BSC] and globally cover about 12% of the Earth's surface. BSCs are a thin cohesive layer assembling microorganisms to soil particles and are often described as the biologically active skin over arid and saline soils (example of BSC in Box 3). BSCs are created by soil microorganisms to protect themselves from the harsh desertic conditions—particularly desiccation—and in the process create hospitable habitats for other organisms and favor plant germination. The microbial communities inhabiting BSCs are very diverse and can comprise bacteria, archaea, viruses, lichens, mosses, algae and fungi, and are usually dominated by cyanobacteria—notably *Microcoleus vaginatus*. In deserts, where plants are sparsely distributed, they represent primary production hotspots, through their atmospheric carbon (C) and nitrogen (N) fixation capacities via photosynthesis and diazotrophy, respectively. The importance of BSCs in global and desert biogeochemical cycling and desert productivity is further highlighted by the fact that about 7% and 50% of all the terrestrial fixed C and N, respectively, has been estimated to be fixed by BSCs. The glue sticking together the soil aggregates in these crusts is made of cyanobacterial filaments, fungal hyphae and extracellular polysaccharides (or exopolysaccharides [EPS]) which are complex sugars and organic polymers excreted by cyanobacteria following photosynthesis, and by numerous other microbes, such as heterotrophic bacteria that feed on organic carbon created by the cyanobacteria. BSCs therefore increase the C pool of otherwise highly oligotrophic desert topsoils, improve their water retention capacity and decrease their erodibility.

Box 3: Microbial mats and biological soil crusts on arid and saline soils

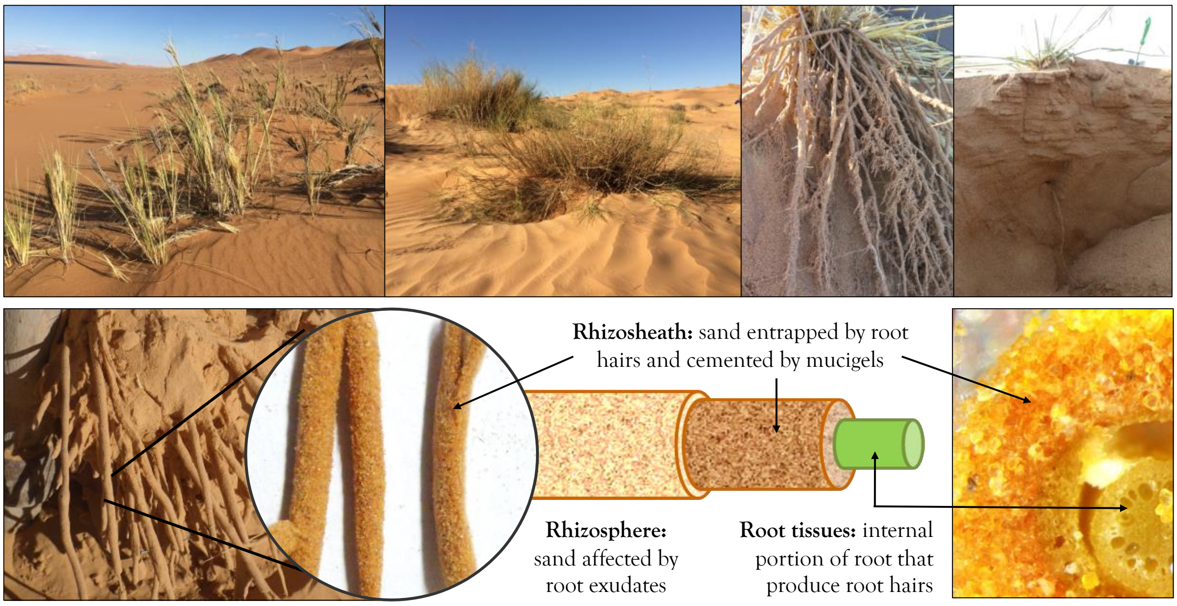


Microbial mats/biological soil crusts covering the saline soil in the Sebkha Al Hnichrat in the south of the Tunisian coast close to the city of Zarzis (**a**). Sebkhas are arid and saline plains generally located in topographical depression, frequently on desert coastlines. The crust/mat forms a uniform and extensive (**b**), mm-thick (**c**) robust carpet-like layer which protects the underlying soil. The soil receives periodical seawater inundations, which allow cyanobacteria to develop crusts/mats, which are then inhabited also by other microorganisms, micro-invertebrates and eventually plants, such as *Salicornia*.

3. ***Xerophytic plants and the rhizosheath biocenosis enhance biodiversity in arid soils.*** Due to the limited rain (< 100 mm per year), only a restricted group of plants are able to survive in deserts; these plants are called xerophytes. To live under the harsh environmental conditions of deserts, these plants evolved specific adaptations that include morphological and physiological changes of both their above- and below-ground compartments (*i.e.*, shoot and root, respectively).

These adaptations allow the plants to optimize the use of the scarce water in the soil and the humidity in the air, as well as to minimize water losses by evaporation. For example, succulent plants store water in their stems and leaves, while shrubs and bushes, which grow in the sandy soils at the edges of desert dunes, develop special and deep root systems that allow the uptake and long storage of large amounts of water. Among these successful adaptative features is the root rhizosheath system; for example, 107 of 130 South African grass species can form rhizosheaths. These are compact structures covering the entire root length made of dense entangled root-hairs entrapping sand grains that are packed together by gluey substances released by the roots. The rhizosheath development is also helped by microorganisms, which colonize the plant root system. The rhizosheath protects root from the dry condition of soil and helps the plant to retain water and nutrients, creating a suitable ecological niche that attracts other organisms (*e.g.*, invertebrates). The rhizosheath-root system represents a 'hot spot' where water and organic matter are enriched with respect to the surrounding barren sand, and microbial diversity flourishes. Plant growth promoting (PGP) functions carried out by microorganisms are also enriched. Such beneficial PGP microorganisms cooperate with the plant root in order to improve the nutritive conditions of the soil (biofertilization), plant growth stimulation (biopromotion), and stress protection (bioprotection) under the harsh conditions of the desert. Such beneficial interactions facilitate plant establishment and stabilize and protect soil from wind erosion. The plant-microbe association in the rhizosheath ameliorates plant drought tolerance. Under the ongoing climate change, rhizosheaths represent a model of xerophytic adaptation of the plant-microbe association for counteracting enhanced aridity and water stress.

Box 4: Rhizosheath-root system in xerophytic desert plant



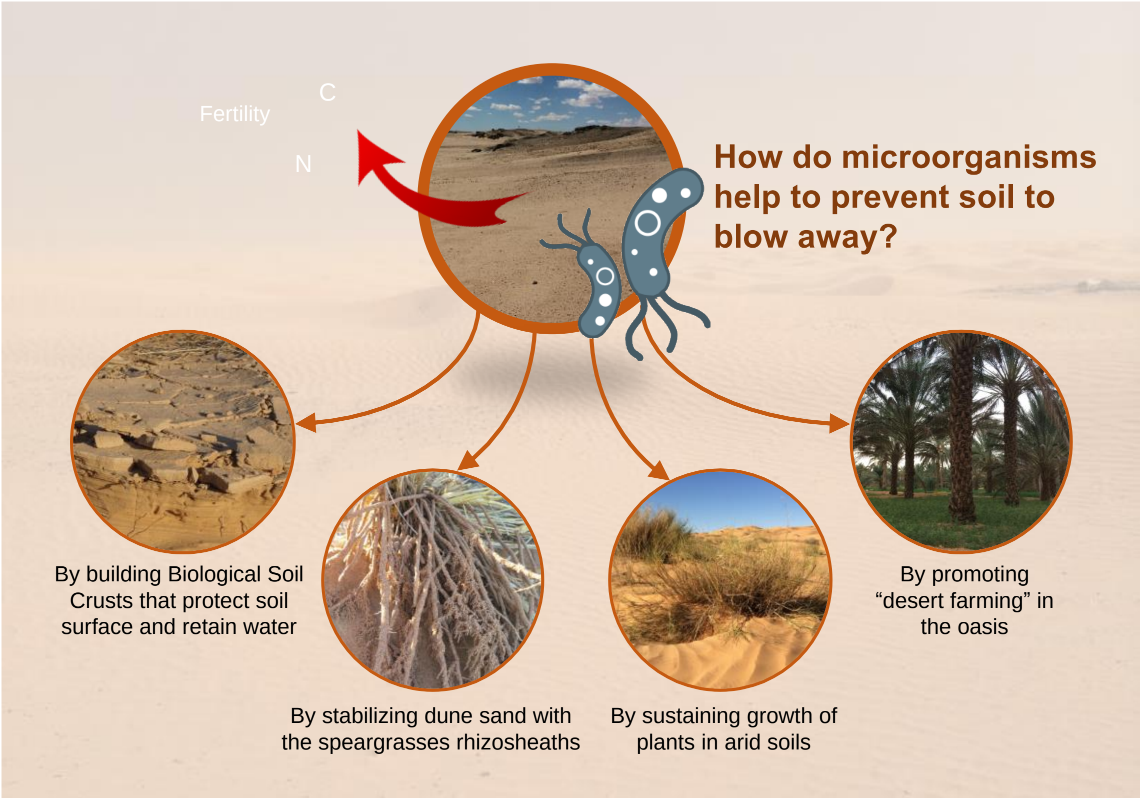
4. ***Agriculture in arid lands, Desert Farming and the role of microorganisms.*** Climate change models are predicting a drastic global increase of arid regions, coupled with an increased demand for water, energy and food of 40-50 percent by 2030. This is a challenging scenario which requires more efficient agriculture systems, especially in areas with scarcity of water. To practice agriculture in arid lands, a priority is to economize water. All available practices directed towards water saving while supporting crop production are encompassed under the practice of Desert Farming. This ancient practice considers a competent use of water, by water reuse,

desalination, and drip irrigation, and the application of traditional agriculture techniques that favor the fertility of soils, including amendment with organic matter and fertilizers and appropriate crop rotation and/or co-cropping. These practices provide important nutrient resources for plants, and favor the development of microorganisms in the rhizosphere (*i.e.*, the thin soil layer attached to the root) and the root endosphere (the internal root tissues). In the few millimeters surrounding the roots, many soil microorganisms are attracted by the abundant and diverse carbon sources released by the roots through exudation and rhizodeposition. Following the growth on these carbon sources the microbial cell density in the rhizosphere can be well above 10^9 cells per gram of soil, much higher than in barren soils devoid of plant roots. Most of these microorgansms are beneficial plant growth promoters (PGP) that provide important services in helping the plant to tolerate water scarcity, increased soil salinity, high temperature, and pathogen attacks. Desert soil microorganisms, which are more adapted to water stress and salinity than microorganisms in fertile soils, can help to enhance plant performance under desertification, and favor agriculture in marginal lands.

5. ***The oasis, a sustainable agroecosystem for human populations in the deserts.*** Oases are unique and highly productive rural cropping systems common within desert regions around the world. By the exploitation of desert farming practices, several different plants are co-cultivated in the oasis, coexisting in space and time and thus representing one of the few remaining multi-cropping agro-ecosystems. This multi cropping agriculture — which has been developed because the isolated oases could not be regularly reached with goods — is a source of diversified food that supports the oasis economy and social activities in the remote areas of deserts. In oases, plants are cultivated by exploiting different vertical layers of vegetations, generally ruled by a top layer of shadowing plants, such as date palms (*Phoenix dactylifera*) that form a dense canopy able to recondition the hot and dry climate of the desert, providing shade, which in turn decreases air temperature, and enhances air moisture.

The environmental conditions created by date palms favor the cultivation of other crops below the canopy, such as olive, almond and pomegranate trees, cereals and leguminous and forage plants, contributing to preserve crop diversity in arid regions. Thus, in an oasis, date palms are the key players determining the suitable conditions for crop cultivation, which, otherwise could not be sustainable. Date palms rely on specific physiological adaptations that help them to cope with desert stressors, including thick trunks capable of retaining large amounts of water, waxy foliage to minimize water losses and long roots to tap into ground water. Date palms — like all plants — are helped by microorganisms. The plant selects and recruits beneficial PGP bacteria and fungi from the surrounding soil that promote plant growth and protect the plant from drought and salinity stresses. It has been shown that, despite the diversity of microorganisms harbored by soils of far apart regions of the desert, date palms tend to attract always the same PGP bacterial and fungal types able to confer such beneficial services. By contributing to keep date palms healthy and productive, these microorganisms also contribute to sustaining the entire oasis agro-ecosystem.

Box 5: Microbial actions contributing to soil properties



Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 13. Take urgent action to combat climate change and its impacts** (*reduce greenhouse gas emissions, mitigate consequences of global warmings*). Microbial soil crusts fix substantial amounts of carbon dioxide and thus contribute to global activities that counteract anthopogenic greenhouse gas emissions. Current technologies cannot directly change the soil microbiome in any significantly beneficial manner. This is a consequence of both the incredible complexity of soil microbiomes, and the enormous scale of global soil ecosystems (but see above). Current soil microbiome manipulation is largely restricted to supplementing relatively small areas of land with 'microbial' cocktails, either pure cultures of Plant Growth Promoting Bacteria or microbial consortia comprising a few different taxa. The value of these approaches is still a matter of intense debate. However, there is a major global effort to find ways and means, including microbial, to reduce desertification and increase productivity of arid lands.
  However, our only immediate option for reducing desertification and the above-ground and below-ground consequences of that process is to stabilize, or reverse, the current trends in global warming and the associated changes in local and regional climates.

- **Goal 15. Take urgent action for land preservation** (*preserve soil structure and water retention in arid ecosystems*). Around one third of the global land surface is affected by land degradation/desertification, which therefore represents one of the greatest environmental challenges we are facing. This is further highlighted by the fact that in the last 40 years one third of arable land surface has been lost to desertification, particularly in Africa. Notably, with desertification soil loses its texture and can be easly blown away by wind. Such soil/sand dust can be transported far away and even to open oceans, where it acts like fertilizer, favoring the blooming of microscopic sea plants that provides nutrients for zooplankton, fish and larger ocean animals. Desert dusts can even have transcontinental effects. For example, the Bodelé depression in the southern Sahara only covers a 75,000 km^2 area (*i.e.*, around as big as the countries of Panama or the Czech Republic) but provides half of the nutrients deposited in the Amazon Rainforest. This amounts to approximately around 20 million tons of dust annualy, and is crucial for the sustainability and luxuriance of the Earth's green lung which is characterized by having soils that are rather nutrient- and mineral-poor.

Soil crusts play an important role against desertification, by diminishing soil erosion by gluing together surface inorganic soil particles and by increasing soil fertility through their water retention and carbon and nitrogen fixation capacities. Soil crusts also mitigate dust formation and dust/sandstorms which can alter climate, human health and many socio-economic sectors, such as agriculture. However, soil crusts are very fragile and often take years to build up. Consequently, their preservation should be improved where they are still in a pristine state, along with their rehabilitation in degraded environments.

Potential Implications for Decisions

1. ***Individual behaviours and initiatives for desert preservation***

Desertification is such a large-scale issue that it is difficult to see how any individual could make a difference. Not only is the process itself truly *continental* in scale, but the processes which drive desertification are truly global in scale. Nevertheless, the combined actions of individuals accumulate and, over time and at a sufficient scale, can bring about change governments in attitudes, in policies, in actions and ultimately in effects as large as control of atmospheric carbon dioxide levels and global temperatures.

2. ***Community policies for desert preservation***

Preserving desert biomes is strictly linked to preservation of the thin surface layer on the desert soil that makes the biological soil crusts. Moreover, deserts are empty harsh spaces that may be viewed as landfill sites for any type of waste. Educational programs should be undertaken to alert people of the delicate nature of the desert ecosystems and biomes, and their potential for contributing to preservation of a healthy planet. To preserve and minimize disturbance and disruption of biological soil crusts, it is fundamental to increase the protection of the fragile desert biomes. For example, regulations could be implemented to limit their accesses by creating protected areas requiring the acquisition of specific permits or to enforce the use of specific footpaths or tracks when hiking or driving therein, respectively.

3. ***National policies for desert preservation***

The future of deserts and their biomes are linked to the future of the climate scenarios. National and international initiatives to limit greenhouse gas emission, global warming and climate change are essential for preserving deserts.

Pupil participation

1. ***Class discussion on the desertification and soil quality preservation***

2. ***Pupil awarness***

Desert areas close to cities are frequently exploited for tourism and experiencing acrobatic driving on sand dunes which disturb the dune structure and the living biomes and the biological soil crusts. Can you think any initiative that individuals may take to preserve soil in arid regions?

The evidence base, further reading and teaching aids

1. Global climate change and desertification: https://www.carbonbrief.org/explainer-desertification-and-the-role-of-climate-change
2. Deserts: https://www.nationalgeographic.org/encyclopedia/desert/?utm_source=BibblioRCM_Row
3. Makhalanyane T.P., Valverde A., Gunnigle E., Frossard A., Ramond J.B., Cowan D.A. 2015. Microbial ecology of hot desert edaphic systems. *FEMS Microbiology Reviews* 39:203–221.
4. Pointing S.B., Belnap J. 2012. Microbial colonization and controls in dryland systems. *Nature Reviews Microbiology* 10:551-562.
5. Marasco R., Mosqueira M.J., Fusi M., Ramond J.-B., Merlino G., Booth J.M., Maggs-Kölling G., Cowan D.A., Daffonchio D. 2018. Rhizosheath microbial community assembly of sympatric desert speargrasses is independent of the plant host. *Microbiome* 6:215.
6. Oases: https://www.nationalgeographic.org/encyclopedia/oasis/
7. Mosqueira M.J., Marasco R., Fusi M., Michoud G., Merlino G., Cherif A., Daffonchio D. 2019. Consistent bacterial selection by date palm root system across heterogeneous desert oasis agroecosystems. *Scientific Reports* 9:4033.
8. Koren I., Kaufman Y.J., Washington R., Todd M.C., Rudich Y., Martins J.V., Rosenfeld, D. 2006. The Bodélé depression: a single spot in the Sahara that provides most of the mineral dust to the Amazon forest. *Environmental Research Letters*, 1:014005.

Glossary

Agricultural productivity refers to the quantity of product produced by crops (*i.e.*, output or crop yield) with a certain quantity of input (water, fertilizer, etc.).

Biogeochemical cycling refers to the succession of biotic and abiotic transformations into different forms that an element (e.g., nitrogen, carbon) or a molecule (e.g., water) will undergo in the different compartments of Earth (atmosphere, biosphere, lithosphere, and hydrosphere).

Biological soil crusts (or BSCs) are living biofilms developing on surface soils, essentially in arid lands, composed of many different microorganisms (mainly bacteria, fungi, moss, and algae). BSC-colonizing microorganisms are protected from otherwise extreme environmental conditions.

C pool defines a system (or reservoir) which can store or release Carbon.

Carbon mineralization is a **carbon sequestration** process by which carbon dioxide (CO_2) is immobilized in minerals such as carbonates (e.g., calcium carbonate [$CaCO_3$]).

Carbon sequestration encompasses all the natural and industrial processes that remove carbon dioxide (CO_2) from the atmosphere.

Climate change refers to all the modification in the chemical composition of the Earth's atmosphere, such as the increament of greenhouse gases like carbon dioxide (CO_2), nitrous oxides (N_2O) and methane (CH_4), that are driven by human activity since the Industrial Revolution. These modifications have led/are leading to global and regional modifications of climates (temperature and precipitation patterns). For examples, with climate change, it is expected that drylands will experience hotter temperatures globally and regional modification in their precipitation patterns (less, more, or no).

Cyanobacteria is a bacterial phylum able to perform **photosynthesis**. Some members of the phylum are also **diazotrophs**.

Desert Farming include all the apractices to develop and maintain agriculture in desert and arid areas; they include a efficent and focused use of water, such as reuse, desalinization, and drip irrigation.

Desert oases are fertile areas (often having date palm grove) in desert or semi-desert environments. They can be wild (no handled by humans) or managed by **desert farming** pratices.

Desertification is a land degradation process of arid lands which become less productive by general loss of vegetation through increase aridity. Climate Change enhances dryland desertification.

Desiccation indicates the process in which all water/moisture is eliminated from something (*e.g.*, soil).

Diazotrophy is the capacity that a group of specific microorganisms (diazotrophs) can perform to fix atmospheric di-nitrogen (N_2) into bioavailable Nitrogen.

Ecological niche refers to the position of a species (micro- and macro-organism) within an ecosystem, *i.e.*, the micro-environment or range of environments with the right conditions for it to be colonized. It also describes the conditions necessary for the species persistence and the ecological role that the species has in the ecosystem.

Endosphere (of plants) defines all the internal tissues of plant, such as root, shoot, leaves.

Erosion is a natural geological process leading to the terrestrial loss material through the action of wind and/or water.

Exopolysaccharides are carbohydrate polymers that are produced and released by many microorganisms; these substances protect the microbial cells and in many cases favor the retention of water.

Food security, as defined by the United Nations' Committee on World Food Security, state the principle that that all people must have access to sufficient, safe, and nutritious food for an active and healthy life.

Marginal lands are all thta lands with limited or no agricultural, often because they have poor soil and/or are located at the edge of deserts. Consequently these lands have little potential for profit and are mostly abandoned.

Microcoleus vaginatus is a **Cyanobacterium** specie that dominates **Biological Soil Crusts**.

Multi-cropping agro-ecosystem is among the most common agricultural methods, particularly in small traditional farms where production is mainly used for the families' subsistence. This systems depend on local crops that are cultivated alltogether to diversify the agriculture production.

Nitrogen fixation generally refers to the fixation of atmospheric nitrogen by diazotrophic microorgnisms into a more assimilable for of nitrogen such as ammonia.

Oligotrophy characterizes an environment poor in nutrient.

Phosphate solubilisation is the process that transforms inorganic/insoluble phosphorus compounds into soluble forms assimilable by plants and other organisms. This process is mainly mediated by phosphate solubilizing bacteria living in the soil.

Photosynthesis is a process performed by living organisms like plants and cyanobacteria that fixes Carbon from the atmosphere (CO_2 gas) using solar energy and water. It generates biomass (in/from the biosphere) and dioxygen.

Plant growth promoters are microorganisms (mainly bacteria and fungi) that favor te gorwth, health and development of plant, especially during stresses, such as drought and salinity.

Primary production is the production of biomass (organic compound) from inorganic molecules such as carbon dioxide (CO_2) and dinitrogen (N_2) gases.
Productivity in (microbial) ecology refers to the production of biomass in an environment.
Rhizosheath is composed by soil particle that cover the root surface; compared to the **rhizosphere**, in this case soil is cemented by the presence of root hairs and mucigels that maintain the overall structure compact and persistent.
Rhizosphere is the narrow portion of soil (few millimeters) that is in contact with the roots; it is directly influenced by plant-root secretions (root exudates) and is rich in nutrients, such as sugars and proteins.
Soil microbiome represents the totally of microorganisms (bacteria, fungi, protozoa and viruses) that live in the soil.
Sustainable Developmental Goals are a collection of 17 global goals designed to be a "blueprint to achieve a better and more sustainable future for all"; these were set in 2015 by the United Nations General Assembly and are intended to be achieved by the year 2030.
Xerophytes plants are species that are adaptated to survive in harsh environment with little ammount of water, such as a desert.