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Desert plants to stop desertification

To succeed, reforestation projects to reclaim once fertile lands need to consider the local abiotic, biotic, and social factors

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Global warming, overgrazing, salinization, and urbanization cause the loss of 12 million hectares of arable land—each year, an area larger than Portugal is turned into unproductive deserts. This massive desertification now affects 1.5 billion people globally and causes 42 billion US$ lost earnings from agriculture. Various huge reforestation projects have been tried to reclaim land lost to desertification mainly by planting millions of trees: the most prominent ones are the 8,000-km-long "Great Green Wall" across the African continent and a similar project in the Gobi desert. However, these megaprojects have encountered major setbacks, which prompted a rethinking of the strategies to reclaim land lost to desertification. Some of the reasons that caused these projects to fail were a disregard for the biological and physical factors specific to arid lands and to the plants adapted to these harsh environments. We therefore posit that a better understanding and use of desert plants and their specific microbiomes could inform more sustainable and resilient reforestation projects in arid and hyperarid regions.

Causes and environmental impact of desertification

Desertification is caused by many factors, and climate change is neither the sole reason nor a main contributor (Arneth *et al*, 2019). The main causes are unsustainable land use driven by overpopulation, increasing urbanization, industrial exploitation, and a massive increase in food demand that, together, slowly degrade drylands and even more fertile lands into infertile deserts (Burrell *et al*, 2020). A key factor is a large-scale deforestation whenever range land is converted to cropland or paddy cultivation. Half of the tropical forests in South America, Africa, and Southeast Asia have already been destroyed, and the remaining soil is slowly degrading. The main drivers are commercial large-scale agriculture, such as cattle ranching or soybean and oil palm plantations, and to a lesser degree local subsistence farming (https://www.fao.org/state-of-forests/en/).

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Another key factor for land degradation is overgrazing by domestic animals feeding on grassland (Fig 1A). It reduces the vegetation cover, damages the soil, and causes erosion and further compaction of top soils (Kéfi *et al*, 2007). The effect of grazing in destroying the vegetation cover has also a negative impact on soil composition and the soil microbial communities involved in carbon and nutrient cycling.

Lastly, overirrigation of arable lands can lead to the salinization of soils if the water is mostly evaporated through plants or directly from the ground. Globally, huge formerly arable areas have been lost to oversalinization followed by desertification notably in Australia, Africa, and the Middle East. The fate of Lake Aral in Central Asia vividly demonstrates how overirrigation by Soviet agriculture to produce cotton not only drained what was the fourth largest lake on the planet, but also caused a massive environmental catastrophe by salinization of once fertile soils followed by desertification.

> *"The main causes of desertification are unsustainable land use driven by overpopulation, increasing urbanization, industrial exploitation and a massive increase in food demand."*

Mitigation strategies

Preventing or reversing desertification requires massive investments at multiple levels, including societal and economic policies to change land use and agricultural practices. Such policies should be put in place at the first signs of desertification as it is much easier and cost-efficient to halt land degradation at an early stage than attempting to reclaim desert lands.

Many strategies to restore desert lands have been tried and tested worldwide. The most popular—and the most visible—is reforestation by planting kilometer-wide green walls of trees in the hope that this consolidates the soil through the extensive root system and thereby generates fertile ground to grow other plants. This approach,

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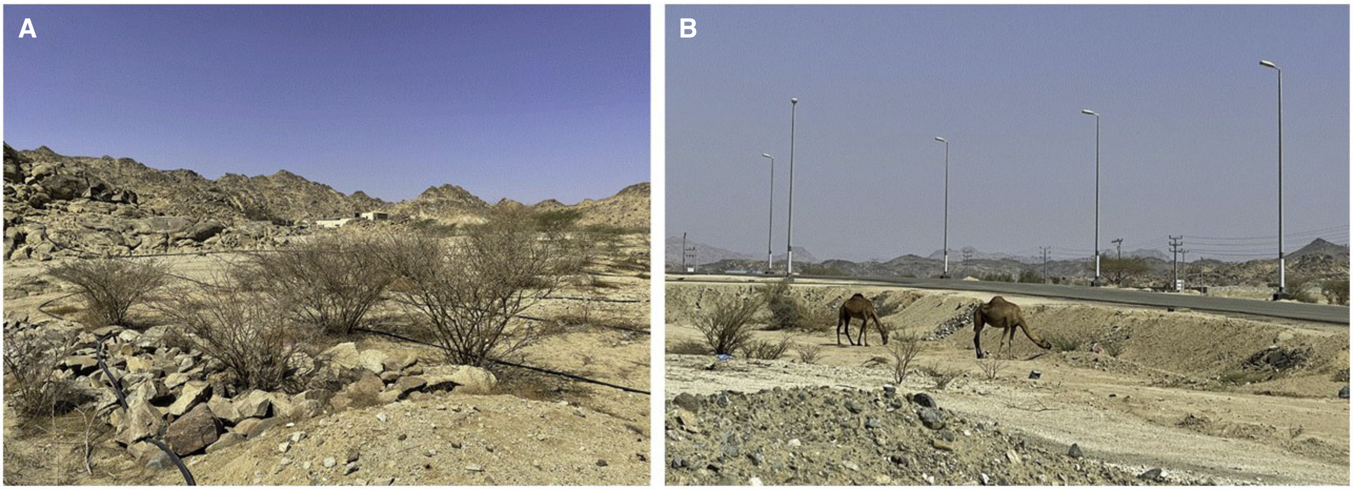

Figure 1. Landscape degradation and desertification. (A) Example of a failed reforestation project with dead trees after irrigation was stopped. (B) Loss of vegetation by camel grazing.

although it might seem effective and certainly is very attractive, requires multibillion-dollar investments, however, and relies heavily on irrigation. Unfortunately, most of the planted trees die as soon as irrigation stops (Fig 1); an example is the 1980 green wall of the Sahel where up to 80% of the planted trees died in some areas (Cernansky, 2021).

"Reforestation was not sustainable because for a number of reasons: the wrong trees, the increasing population growth and land use, inappropriate farming practices, and last but not least, the effects of climate change."

The strategy was not sustainable because of a number of reasons: the wrong trees, the increasing population growth and land use, inappropriate farming practices, and last but not least, the effects of climate change. Learning from the failures, reforestation projects have shifted their approach from simple tree-planting projects to a network of locally sourced sustainable land management practices. One promising method for regreening the desert is termed "planting pits" also called Zai (http://soilinternational.com/zai/; https://www.youtube.com/watch?v=x28NpUZjmN8). It originated in Burkina Faso and included digging holes in the soil before seeding, which improves water retention during dry periods, more efficient use of rainwater, and better uptake of nutrients.

Yet, the most sustainable and promising solutions are emerging from the study of desert biomes: soils, microbiomes, and indigenous desert plants. Exploiting their particular properties should be instrumental to achieve more sustainable solutions than what has been tried and tested so far. Indeed, the use of native tree species in Nigeria and Northern Ethiopia helped to restore ecosystems by improving soil quality and reclaim land lost to desertification (Carey, 2020). This knowledge, combined with modern irrigation and monitoring technologies, will be used in the recently launched Middle East Green Initiative, the aim of which is to restore an area equivalent to 200 million hectares of degraded land across the Middle East by planting 50 billion trees (https://www.vision2030.gov.sa/v2030/v2030-projects/middle-east-green-initiative/).

Desert plants to restore rangeland

Desert plants in particular may well be the key factor for any reforestation project to have success. These "desert survivors" have adapted their morphology, architecture, and tissues to infertile soils with high salinity and poor nutrients (Kirschner *et al*, 2021), which makes them ideal for restoring desert lands. Moreover, desert plants include a wide range of species from grasses to shrubs to trees that can be used not only for restoring lands but also for landscaping to substitute commonly used species that require constant irrigation (Fig 2).

"Desert plants may well be the key factor for any successful reforestation project."

The desert flora consists of annual, ephemeral, and perennial species. Annual plants have a short life cycle of less than a year, whereas ephemeral plants emerge only after rare rains and finish their life cycle before the onset of the new drought period. These plants live their short lives but increase the survival of their offspring with thick seed coats to resist dry conditions and high temperatures. Many seeds or embryos stay dormant until a rare rain event occurs that initiates their short life cycle.

Finally, perennial trees and shrubs are the hardest adaptations that can withstand long periods of drought and heat because of their ability to reduce transpiration and evaporation (Gibbens & Lenz, 2001). The vast majority have a narrow leaf morphology as a strategy to reduce the transpiration area and prevent water loss. During extreme drought, many woody plants lose most of their leaves until water becomes again available. Shrubs and bushes have shallow root systems that expand underneath the soil surface to ensure easy access to surface

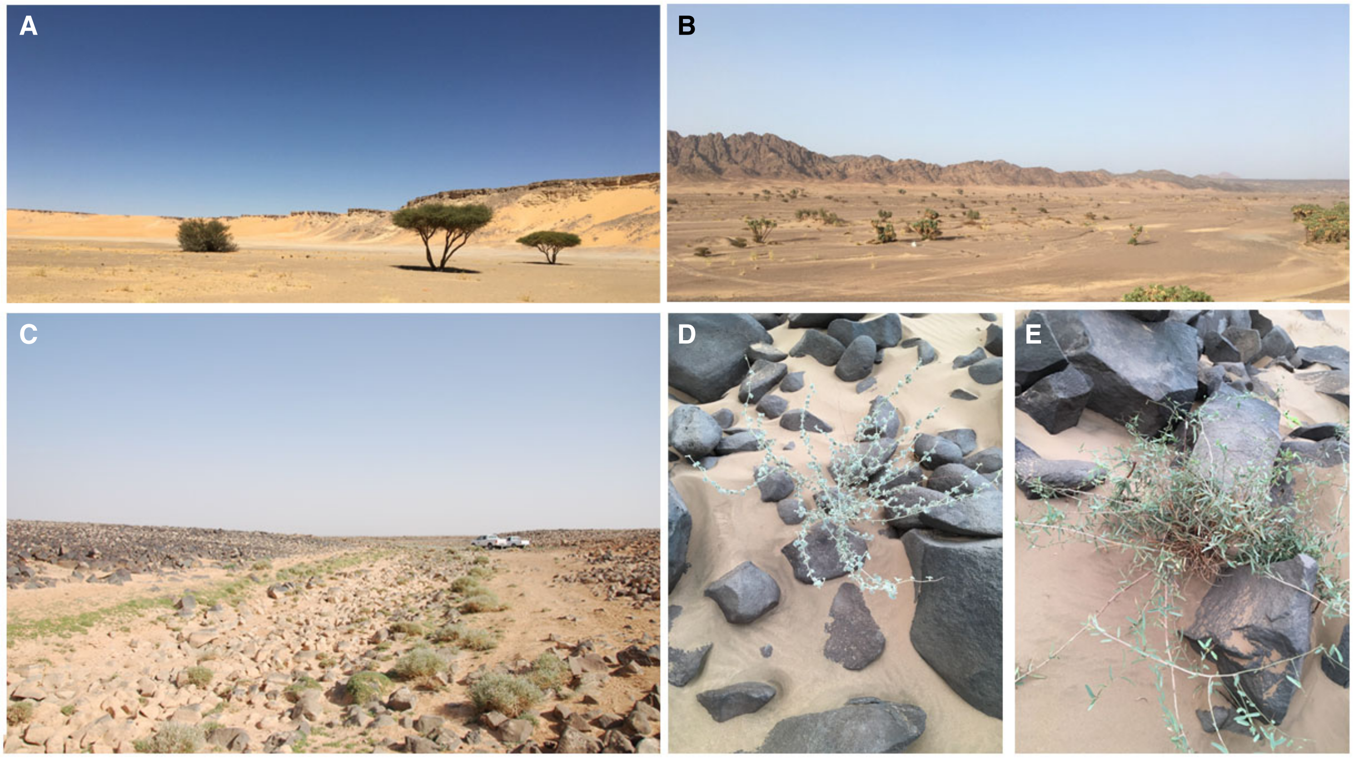

Figure 2. Landscapes with desert plants ranging from perennial trees (A, B) and shrubs (C) to annual plants (D, E).

moisture. Some desert plants also have tap roots that reach a dozen of meters into the soil in search of water (Kirschner *et al*, 2021; see Further reading).

Another crucial factor for withstanding long periods of high temperatures and water scarcity is the photosynthesis mode deployed: so-called C3 plants include the vast majority of land plants; the C4 photosynthesis mode is more common among grasses while the CAM mode is mostly used by species adapted to arid habitats (see Further reading). Under temperate environmental conditions, C3 plants perform best with a high rate of photosynthesis as energy capture by chlorophyll and carbon fixation in the Calvin cycle takes place in the same tissues. The price for this efficiency is water loss through transpiration as C3 plants have to keep their stomata open for gas exchange. C4 plants have a competitive advantage under high light intensity, high temperatures, and water scarcity as the energy capture and Calvin cycle take part in different tissues. C4 plants store the energy captured from sunlight in mesophyll cells via the intermediate malate, which is then converted to pyruvate and CO_2 to supply the Calvin cycle in the bundle sheet cells. This creates local high CO_2 concentrations without the need for gas exchange and thereby reduces transpiration and water loss during the hottest part of the day.

CAM plants, notably cacti, are well-adapted perennial desert plants and are known for their highly efficient water management. CAM plants perform photosynthesis during the day with their stomata closed and store the energy as malate. They only open their stomata during the night to exchange CO_2 and O_2 with minimal transpiration losses and use the stored malic acid to feed the Calvin cycle. Their thick stems, protected by a thick and waxy cuticle, allow them to store enough water to survive even several years of drought. Succulent plants, however, constitute only a small fraction of desert plants. Interestingly, the vast majority of desert plants do not have obvious structures for water storage (Gibson, 1998).

Recent studies have shown that mixed communities of desert C3 and C4 plants can improve the survival of C3 plants albeit at the expense of C4 species. Despite this drawback, using a mix of native desert C3 and C4 plants might improve efforts to help restoring desert lands by increasing the overall production of biomass. Another approach would be engineering C3 plants with C4 or CAM traits (Cui, 2021); indeed, attempts to introduce a functional C4 pathway into rice, a C3 plant, have been successful. Such approaches could be adopted for future reforestation strategies to adapt crop plants to arid and semi-arid conditions.

Trees or bushes?

Planting trees in the desert seems like a straightforward solution that is also highly popular and can be easily communicated to local communities and funders alike. However, most artificially, planted trees struggle to survive once irrigation is stopped owing to their high water consumption—depending on the size, a typical tree consumes several hundred liters of water/day. Indeed, trees are rare in deserts given the limited availability of water, but those trees that are adapted to arid conditions can well serve "greening" projects without increasing the overall demand for water (Fig 1B). Acacias, for example, are native desert trees with economic importance as they produce Arabic gum. The Gaf tree requires only scarce amounts of water and grows rapidly, and the evergreen Juniper tree is also well-adapted to deserts.

However, deserts are typically not covered by forests and trees are few and far between. Instead, the dominant plants in arid and semi-arid areas are drought-enduring bushes among a few scattered trees. Bushes can form root systems as large as those of trees and are therefore as good in stabilizing soil, but typically use only 10% of the amount of water than trees do. Hence, desert bushes should be considered as a viable alternative for halting desertification and reclaiming land.

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Mitigating desertification through land restoration

During the past decade, the growing awareness of the need to restore desert lands has inspired the development of new technologies to build more resilient landscapes. One promising eco-mechanical solution to mitigate desertification might be the transformation of sand into soil: the general idea is to convert sand into a substrate with similar mechanical and ecological properties as soil (Yi *et al*, 2022). This conversion is achieved by mixing sand with a modified sodium carboxymethyl cellulose (CMC) solution and fertilizer. This artificial soil can retain water, minerals, microbes, and nutrients, switches its rheological state from soft solid when wet into solid during dry seasons, and thus provides an ideal substrate for plant growth. The technology has been successfully used in the Ulan Buh Desert in the Mongolian autonomous region. Application of the sand/CMC mixture to a sandy 1.6 hectare plot transformed the region into fertile land to grow tomatoes, rice, and other crops. Sand conversion has also been applied in other deserts including the Taklimakan, the Middle East, and the Sahara Desert.

Another promising technology is liquid nano clay (LNC): sand particles coated with clay which allows them to hold water. In 2018, this technology was successfully tested in UAE at the International Center for Biosaline Agriculture. Lands treated with LNC retained almost 50% more water than nontreated land (https://www.desertcontrol.com/liquidnanoclay).

Superhydrophobic sand was also developed to maximize water retention efficiency (Chen *et al*, 2017). The technology is based on coating sand granules with a nanoscale layer of paraffin wax. The application of a thick layer of superhydrophobic sand over normal soil reduced evaporation and increased soil moisture, which increased crop growth and minimized water use.

Land restoration using desert soil and plant microbiomes

Apart from the physical properties of the soil, a number of biotic factors shape the lives of all organisms in the desert. Sessile organisms such as plants, fungi, and microbes are especially affected by low precipitation and high fluctuations in temperate and solar radiation. These factors increase water evaporation and accumulation of salts in the soil and together shape the biomes of desert soils.

> *"Desert root microbiomes [. . .] provide a crucial factor for replanting arid and hyperarid areas with a minimum of attention."*

Since the development of next-generation sequencing, our understanding of the structure and complexity of soil biomes has expanded exponentially. Comparing multiple data sets from arid with nonarid soils revealed clear differences in the microbiome structures, namely that arid soils in general display a lower relative phyla abundance (Vásquez-Dean *et al*, 2020). Moreover, arid soils have a higher abundance of Actinobacteria and a lower abundance of Proteobacteria, Cyanobacteria, and Planctomycetes. Although similar data on the fungal and other biome data are scarcely available, we can also expect major differences in these biomes (see Further reading).

It is now well-known that the soil microbiome is closely associated with plants as these are often the only source of carbohydrates for microorganisms. Apart from microorganisms in the zone around the root (root rhizosphere), plants also host a large variety of microorganisms inside the plant root (root endophytes). Although the root rhizosphere is strongly shaped by the composition, water availability, pH, and electrical conductivity of the respective soil, plants actively shape the structure and complexity of the soil microbiome, while the plant endophytic microbial communities are also strongly determined by host genotype (Alsharif *et al*, 2020).

> *"The soil–plant-micro-/macrobiome forms an integral ecosystem where all parts have to work together, which may explain the failure of reforestation projects that focused only on one aspect of the system, namely trees."*

Recent studies show that a large range of taxonomically distinct desert root microbes can improve the water and nutrient status and the fitness of non-native crops under arid conditions (Alsharif *et al*, 2020). A common feature of all these endophytic root microbes is that they exert a massive effect on root morphogenesis, often doubling root biomass by enhancing the number of lateral roots and root growth. Desert root microbiomes thereby provide a crucial factor for replanting arid and hyperarid areas with a minimum of attention (Saad *et al*, 2020). Many of these microbes can transfer their beneficial traits to other crops, making desert plant microbiomes also a treasure trove for adapting agriculture to the effects of climate change.

Conclusions

Desertification of land is caused by continued population growth and changes in land use, inappropriate farming practices, and increasingly the effects of climate change. Since human practices are the main cause of desertification, it is up to us humans to stop these activities. For instance, land restoration through planting or preventing grazing was shown to be more efficient when involving the local community. By way of example, the Middle East EcoPease initiative created the Jordan Eco-park in the Jordan

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Desert soil and microbiome adaptations

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Technological solutions to revegetate deserts

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river valley in 2004 and transformed bare land into a functioning wooded ecosystem by planting trees and implementing strict limitations to farming and grazing by involving the local community.

In addition, more land restoration, reforestation, and changes in agricultural practices are necessary to turn land back into functioning agroecosystems. Whereby drylands that have retained some vegetation are easier to convert, hyperarid desert ecosystems require a more sophisticated approach than merely planting trees. The soil–plant-micro-/macro-biome forms an integral ecosystem where all parts have to work together, which may explain the failure of reforestation projects that focused only on one aspect of the system, namely trees. In general, it appears that using native, locally adapted vegetation provides the best strategy for revegetation. In addition, such projects need to consider the physical, chemical, and biome structure of the particular soil and match these with the respective plant species. The Green Wall of the Sahel and other reforestation projects, despite their failures, have been important and worthwhile efforts to halt the ongoing desertification in many parts of the world, but it needs a more informed strategy, based on scientific evidence and novel technologies, to make these work.

Disclosure and competing interests statement

The authors declare that they have no conflict of interest.

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