Hot Desert Microbiology: Perspectives in a Warming World

12

Jean-Baptiste Ramond and Don A. Cowan

Abstract

Deserts are the most dominant terrestrial environments as they cover over a third of the Earth's emerged surface. These arid ecosystems further influence global biogeochemical cycling particularly via the emission of dust. These dust clouds can travel thousands of kilometers and fertilize very distant environments as well as intensify global warming. This is concerning as desert surfaces are expanding with climate change. This concluding chapter therefore briefly discusses possible novel research avenues that desert microbial ecologist could follow in the context of climate change.

Deserts biomes experience a very wide range of macro-climatic conditions. They may be either hot (e.g., the Sahara Desert) or cold (the Antarctic McMurdo Dry Valleys), may be coastal (e.g., the Atacama and Namib Deserts) or inland (e.g., Mojave and Gobi Deserts) and may be low or high altitude. However, the critical common feature shared by desert biomes is a general deficiency in water availability. To be considered a desert, an environment must present an aridity index (AI), defined as the ratio of Precipitation (P) over Potential Evapotranspiration (PET) [AI=P/PET], below 0.65. The AI allows a further sub-classification of the aridity

J.-B. Ramond (✉)
Department of Molecular Genetics and Microbiology, Pontificia Universidad Católica de Chile, Santiago, Chile

Centre for Microbial Ecology and Genomics, Department of Biochemistry, Genetics and Microbiology, University of Pretoria, Pretoria, South Africa
e-mail: jbramond@bio.uc.cl

D. A. Cowan
Centre for Microbial Ecology and Genomics, Department of Biochemistry, Genetics and Microbiology, University of Pretoria, Pretoria, South Africa

status of drylands from dry-subhumid (0.5 < AI <0.65) to hyperarid (AI <0.05). Using these AI-based definitions, drylands/deserts represent the most dominant biome on Earth, covering approximately 40% of the planet's terrestrial surface and being the only biome present on the six continents. To obtain a better understanding of the climatic and geomorphological features that give rise to hot deserts globally, the reader is referred to Chap. 1 of this book.

Given the scale of dryland coverage on terrestrial Earth, a comprehensive understanding of how these dominant ecosystems function is highly relevant at the planetary scale. The chapters compiled in this book provide a comprehensive "*microbes-eye view*" on how these fragile ecosystems are driven by microbially-mediated processes. This is further emphasized by the fact that our species, *Homo sapiens,* the most widespread (and devastating; IPCC 2021) ecosystem engineer on the planet, has a high socioeconomic dependence on dryland ecosystems. More than 2 billion humans, mostly from poor and developing countries are potentially impacted by dryland expansions (desertification processes), according to the United Nations Decade for Deserts and the fight against Desertification (UNDDD) 2010–2020 reports (http://www.un.org/en/events/desertification_decade/whynow.shtml).

Deserts have a substantial impact on the overall functioning of planet Earth (Pointing and Belnap 2014; Kok et al. 2017). Annually, billions of tons of soil-derived dust are emitted from deserts and dispersed at very large scales, with significant impacts on local biogeochemistry and climate (Herut et al. 2002; Jickells et al. 2005; Kellogg and Griffin 2006; Bristow et al. 2010; Gonzalez-Martin et al. 2014; Pointing and Belnap 2014; Kok et al. 2017; Šikoparija 2020). Remarkably, the phosphorous-deficient Amazon Basin in South America, which is the most productive region in the world, receives a significant amount of phosphorous (P) from a relatively small area in the southern Sahara in Chad, the Bodélé Depression of around 10,800 km^2; circa the surface of Jamaica or Lebanon (Bristow et al. 2010). Some 6.5 Tg of Fe and 0.12 Tg of P [1 Tg = 10^9 kg] are emitted each year from the Bodélé Depression, fertilizing the otherwise oligotrophic Atlantic Ocean or the other P-starved Amazon environments (Bristow et al. 2010). Similarly, the dust aerosols emitted by Asian deserts have been shown to cross the Pacific Ocean and even reach the eastern coast of the north America (Kellogg and Griffin 2006), a journey of over 15,000 km. Desert dust aerosols may even participate in global warming (Kok et al. 2017), a cause for concern given that global desert surface areas are increasing with climate change (e.g., Huang et al. 2016, 2017). Desert soil stabilization via the restauration of microbial-dominated biological soil crusts clearly represents a relevant strategy that could be implemented to mitigate the impact of climate change at both the desert biome and the global Earth system scales (e.g., Chap. 3; Bowker 2007; Tucker et al. 2020). Given that BSCs represent N and C fixation hubs in such environments, such a strategy would have a beneficial effect on hot desert primary production, as outlined in Chaps. 3 and 7.

In a world hit by the worst pandemic of modern record, it is also noteworthy that cross-continental desert dust transport events represent potential human and plant health hazards as exogenous pathogens (particularly spore-forming microorganisms)

may hitch-hike on dust particles and colonize/affect new hosts (Griffin 2007; Gonzalez-Martin et al. 2014; Zhang et al. 2016; Salawu-Rotimi et al. 2021). In this context, the recent advances in microbial aerobiology—particularly meta'omics' (e.g., Archer and Pointing 2020; Archer et al. 2021; Maki et al. 2021; Chap. 2)—represents a key future avenue of research for desert microbial ecology.

In addition to water deficiency, a range of other abiotic stresses are imposed on desert (micro)biota. These may include (hyper)oligotrophy, high soil salinity, high UV irradiation, and high daily and seasonal temperature fluctuations (Noy-Meir 1973). As a result, microorganisms are often referred to as the main driving forces of hot desert biogeochemical cycling (Pointing and Belnap 2012; Makhalanyane et al. 2015; Cowan et al. 2020). Chap. 7 summarizes the data indicating how microbial communities from different desert biotopes perform key steps of the C, N, and P cycles. There is even a growing body of evidence demonstrating that desert BSCs are crucial for the cycling of S (e.g., Qi et al. 2021; Zhang et al. 2021). Indeed, as clearly described in the various chapters of this book—and contrary to historical belief[1]— these depauperate ecosystems are populated by a wide array of taxa (e.g., Chaps. 3– 9). Diverse, active, and highly adapted microbial communities have successfully colonized the various niches present in hot deserts, from exposed desert pavements to cryptic refuge niches (such as hypo/endoliths; Chaps. 3–9; Cowan et al. 2020). Even the harshest of desert ecosystems, such as in the most hyperarid regions of the Atacama and Namib Deserts, are colonized by a wide range of active microbial taxa (Gunnigle et al. 2014, 2017; Schulze-Makuch et al. 2018; León-Sobrino et al. 2019; Chaps. 4 and 9). The unique and specialized adaptations of microorganisms to the polyextreme conditions imposed by desert environments—many of which are described in Chap. 10—are exemplified by the recent discovery of the microbial metabolic capacity for harvesting atmospheric trace gasses such as H_2 and CO, effectively unlimited resources in otherwise depauperate environments, for energy and biomass production (e.g., Ji et al. 2017; Jordaan et al. 2020). The observation that aerobic H_2 oxidation is "hydrogenic" (water-producing: Ortiz et al. 2021) offers the intriguing and potentially paradigm-changing possibility that desert soil microbial communities generate their own water! The extent to which metabolic hydrogenesis contributes to the water budgets of desert soil microbiomes, and whether this process is capable of supporting basal cellular metabolism (or even higher desiccation-sensitive metabolic functions such as photosynthesis and cell division) is currently unknown.

Nevertheless, this recent discovery strongly suggests that, within the many desert niches described in this book, new metabolic processes may remain to be discovered,

---

[1]In 1903, when Captain Scott first discovered the Dry Valleys in Antarctica, he wrote "*It is worthy to record, too, that we have seen no living thing, not even a moss or a lichen; all that we did find, far inland amongst the moraine heaps, was the skeleton of a Weddell seal, and how that came there is beyond guessing. It is certainly a valley of the dead; even the great glacier which once pushed through it has withered away*" (Scott 1907). Yet this Mars-like environment unarguably harbors diverse and active microbial communities (e.g., Lee et al. 2012; Chan et al. 2013; Ortiz et al. 2020; Canini et al. 2021; Chap. 10).

thanks to microbial metabolic ingenuity and plasticity when confronted with environmental extremes. The latest high-resolution and high-throughput methods used to study (desert) environmental microbial communities, which are described in Chap. 2, could be central to such discoveries. It is an exciting prospect that such discoveries could lead to the future development of new biotechnologies and even improvements in desert farming (Marasco et al. 2012; Bull et al. 2016; Chap. 8).

However, the world's climate is clearly changing and, in general, desert regions are predicted to become hotter and drier (Huang et al. 2016, 2017). For the first time, the most recent IPCC report clearly states that climate change is an anthropogenic phenomenon: "*It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.*" and "*Each of the last four decades has been successively warmer than any decade that preceded it since 1850*" (IPCC 2021). This global temperature increase is clearly shown in Fig. 12.1, a 20-year comparison of global temperature anomalies in 2001, compared to 2021. Furthermore, 50 °C and above temperatures are now measured at high frequencies globally (Fig. 12.2; Di Luca et al. 2020) and are not limited to drylands. In June 2021, a record high 49.5 °C was measured in British Columbia (Canada) at a latitude of 50.2333° N!
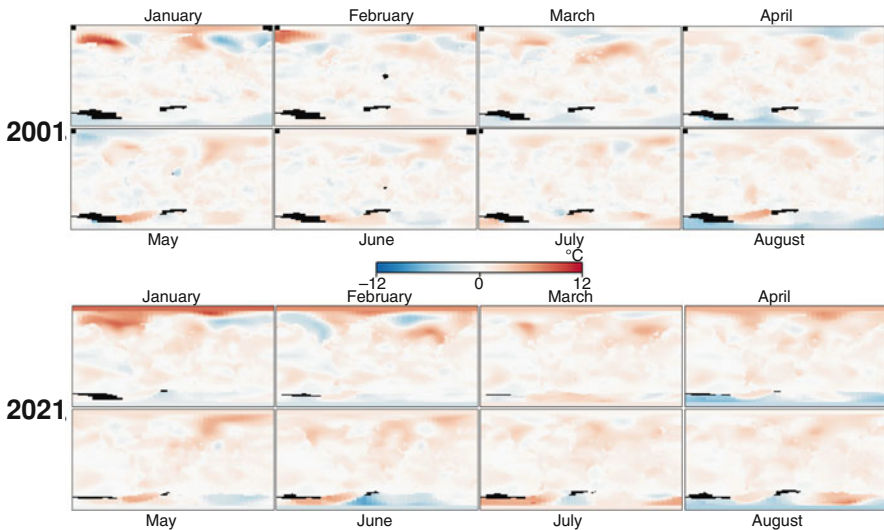
Fig. 12.1 Maps of the monthly global temperature anomalies on Earth from January to August in 2001 and 2021. Imagery produced by the NASA Earth Observations team based on data provided by the NASA Goddard Institute for Space Studies (GISS). Downloaded from https://neo.sci.gsfc.nasa.gov/ on the 6th of October 2021. The maps depict how much warmer (i.e., redder) or colder (i.e., bluer) a region may be in a given month compared to the norm for that same month in the same region from 1951 to 1980. These maps do not depict absolute temperature but instead show temperature anomalies, or how much it has changed. The source data for these images is 2 × 2 degrees—or 180 × 90 pixels

Fig. 12.2 Photograph of a bus stop in the suburbs of Madrid (Spain) on the 14th of August 2021 indicating a temperature of 50 °C (!). *Photo courtesy Mr. José Luis Corbacho*

In heating steadily warming world, can hot desert microbial communities maintain their essential ecosystem functions? This is a critical question, the answer to which requires both a qualitative and quantitative understanding of the functions of desert soil microbiomes, and how such functions may change with changes in water availability and temperature regimes. These two factors are intimately interconnected: increased temperatures will elevate rates of evapotranspiration and decrease mean desert soil moisture contents. In habitats where water-stress is the dominant driver of microbial community structure and function (Makhalanyane et al. 2015), it is confidently predicted that increased mean temperatures will negatively impact microbial communities and the processes they mediate (Neilson et al. 2017; Jansson and Hofmockel 2020). Temperature rises in African and North America deserts have already been shown to reduce the photosynthetic rates in

lichens (Maphangwa et al. 2012) and mosses (Grote et al. 2010), and to significantly decrease biological soil crust cover (~ 44% in 4 years) at two semiarid sites in Spain (Maestre et al. 2013).

However, climate change and the associated regional warming, despite being global phenomena (IPCC 2014, 2021), will have locally specific impacts (Faramarzi et al. 2013; IPCC 2014). Different deserts and the different habitats of each desert harbor unique microbial assemblages that may react differently to thermal and xeric impacts; i.e., may exhibit different degrees of structural and functional resilience (Caruso et al. 2011; Johnson et al. 2017; Chaps. 10 and 11). Consequently, a global effort is necessary to evaluate the impacts of increasing temperatures in each of the Earth's hot deserts, by cataloging and understanding the responsiveness of the different microbial communities, and the way in which such responses affect ecosystem services. This is particularly relevant, given that climate models often lack microbially-mediated data (Treseder et al. 2012; Jansson and Hofmockel 2020). Apart from higher seasonal temperatures (Fig. 12.1), climate change is also predicted to lead to hydrological cycle discrepancies in hot deserts, i.e., longer droughts, and with fewer but more intensive precipitation events (Faramarzi et al. 2013; IPCC 2014, 2021). In this context, the studies summarized in Chap. 11 provide critical information on how hot desert microbial communities may react to changes in water inputs.

Our conclusion, supported by the comprehensive chapters contributing to this text, is that the past decades of research on desert soil ecosystems using the latest and most sophisticated *omics* technologies have done much to help us understand the structure and functional capacity of desert soil microbiomes. We also conclude that there remain huge gaps in our understanding of these fascinating systems, particularly relating to the quantitative aspects of soil microbiome function and their responsiveness to the abiotic variables to which they are exposed. The next two decades of research on desert soil microbiomics may be even more exciting that the last!

References

Archer SD, Pointing SB (2020) Anthropogenic impact on the atmospheric microbiome. Nat Microbiol 5(2):229–231

Archer S, Lee K, Caruso T, Leung M, Tong X, Hinchliffe G, Maki T, Santl-Temkiv T, Warren-Rhodes K, Gomez-Silva B et al. (2021) Diverse recruitment to a globally structured atmospheric microbiome

Bowker MA (2007) Biological soil crust rehabilitation in theory and practice: an underexploited opportunity. Restor Ecol 15(1):13–23

Bristow CS, Hudson-Edwards KA, Chappell A (2010) Fertilizing the Amazon and equatorial Atlantic with west African dust. Geophys Res Lett 37(14):L14807

Bull AT, Asenjo JA, Goodfellow M, Gómez-Silva B (2016) The Atacama Desert: technical resources and the growing importance of novel microbial diversity. Annu Rev Microbiol 70: 215–234

Canini F, Geml J, D'Acqui LP, Buzzini P, Turchetti B, Onofri S, Ventura S, Zucconi L (2021) Fungal diversity and functionality are driven by soil texture in Taylor Valley, Antarctica. Fungal Ecol 50:101041

Caruso T, Chan Y, Lacap DC, Lau MC, McKay CP, Pointing SB (2011) Stochastic and deterministic processes interact in the assembly of desert microbial communities on a global scale. ISME J 5(9):1406–1413

Chan Y, Van Nostrand JD, Zhou J, Pointing SB, Farrell RL (2013) Functional ecology of an Antarctic dry valley. Proc Natl Acad Sci 110(22):8990–8995

Cowan DA, Hopkins DW, Jones BE, Maggs-Kölling G, Majewska R, Ramond JB (2020) Microbiomics of Namib Desert habitats. Extremophiles 24(1):17–29

Di Luca A, de Elía R, Bador M, Argüeso D (2020) Contribution of mean climate to hot temperature extremes for present and future climates. Weather Clim Extremes 28:100255

Faramarzi M, Abbaspour KC, Vaghefi SA, Farzaneh MR, Zehnder AJ, Srinivasan R, Yang H (2013) Modeling impacts of climate change on freshwater availability in Africa. J Hydrol 480: 85–101

Gonzalez-Martin C, Teigell-Perez N, Valladares B, Griffin DW (2014) The global dispersion of pathogenic microorganisms by dust storms and its relevance to agriculture. Adv Agron 127:1–41

Griffin DW (2007) Atmospheric movement of microorganisms in clouds of desert dust and implications for human health. Clin Microbiol Rev 20(3):459–477

Grote EE, Belnap J, Housman DC, Sparks JP (2010) Carbon exchange in biological soil crust communities under differential temperatures and soil water contents: implications for global change. Glob Chang Biol 16(10):2763–2774

Gunnigle E, Ramond JB, Frossard A, Seeley M, Cowan D (2014) A sequential co-extraction method for DNA, RNA and protein recovery from soil for future system-based approaches. J Microbiol Methods 103:118–123

Gunnigle E, Frossard A, Ramond JB, Guerrero L, Seely M, Cowan DA (2017) Diel-scale temporal dynamics recorded for bacterial groups in Namib Desert soil. Sci Rep 7(1):1–12

Herut B, Collier R, Krom MD (2002) The role of dust in supplying nitrogen and phosphorus to the Southeast Mediterranean. Limnol Oceanogr 47(3):870–878

Huang J, Yu H, Guan X, Wang G, Guo R (2016) Accelerated dryland expansion under climate change. Nat Clim Chang 6(2):166–171

Huang J, Li Y, Fu C, Chen F, Fu Q, Dai A, Shinoda M, Ma Z, Guo W, Li Z, Zhang L (2017) Dryland climate change: recent progress and challenges. Rev Geophys 55(3):719–778

IPCC (2021) Summary for policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge. In Press

IPCC (Intergovernmental Panel on Climate Change) (2014) Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. Core writing team, pp. 1–151

Jansson JK, Hofmockel KS (2020) Soil microbiomes and climate change. Nat Rev Microbiol 18(1): 35–46

Ji M, Greening C, Vanwonterghem I, Carere CR, Bay SK, Steen JA, Montgomery K, Lines T, Beardall J, Van Dorst J, Snape I (2017) Atmospheric trace gases support primary production in Antarctic desert surface soil. Nature 552(7685):400–403

Jickells TD, An ZS, Andersen KK, Baker AR, Bergametti G, Brooks N, Cao JJ, Boyd PW, Duce RA, Hunter KA, Kawahata H (2005) Global iron connections between desert dust, ocean biogeochemistry, and climate. Science 308(5718):67–71

Johnson RM, Ramond JB, Gunnigle E, Seely M, Cowan DA (2017) Namib Desert edaphic bacterial, fungal and archaeal communities assemble through deterministic processes but are influenced by different abiotic parameters. Extremophiles 21(2):381–392

Jordaan K, Lappan R, Dong X, Aitkenhead IJ, Bay SK, Chiri E, Wieler N, Meredith LK, Cowan DA, Chown SL, Greening C (2020) Hydrogen-oxidizing bacteria are abundant in desert soils and strongly stimulated by hydration. Msystems 5(6):e01131–e01120

Kellogg CA, Griffin DW (2006) Aerobiology and the global transport of desert dust. Trends Ecol Evol 21(11):638–644

Kok JF, Ridley DA, Zhou Q, Miller RL, Zhao C, Heald CL, Ward DS, Albani S, Haustein K (2017) Smaller desert dust cooling effect estimated from analysis of dust size and abundance. Nat Geosci 10(4):274–278

Lee CK, Barbier BA, Bottos EM, McDonald IR, Cary SC (2012) The inter-valley soil comparative survey: the ecology of Dry Valley edaphic microbial communities. ISME J 6(5):1046–1057

León-Sobrino C, Ramond JB, Maggs-Kölling G, Cowan DA (2019) Nutrient acquisition, rather than stress response over diel cycles, drives microbial transcription in a hyper-arid Namib Desert soil. Front Microbiol 10:1054

Maestre FT, Escolar C, de Guevara ML, Quero JL, Lázaro R, Delgado-Baquerizo M, Ochoa V, Berdugo M, Gozalo B, Gallardo A (2013) Changes in biocrust cover drive carbon cycle responses to climate change in drylands. Glob Chang Biol 19(12):3835–3847

Makhalanyane TP, Valverde A, Gunnigle E, Frossard A, Ramond JB, Cowan DA (2015) Microbial ecology of hot desert edaphic systems. FEMS Microbiol Rev 39(2):203–221

Maki T, Lee KC, Pointing SB, Watanabe K, Aoki K, Archer SD, Lacap-Bugler DC, Ishikawa A (2021) Desert and anthropogenic mixing dust deposition influences microbial communities in surface waters of the western Pacific Ocean. Sci Total Environ 719:148026

Maphangwa KW, Musil CF, Raitt L, Zedda L (2012) Experimental climate warming decreases photosynthetic efficiency of lichens in an arid south African ecosystem. Oecologia 169(1):257–268

Marasco R, Rolli E, Ettoumi B, Vigani G, Mapelli F, Borin S, Abou-Hadid AF, El-Behairy UA, Sorlini C, Cherif A, Zocchi G (2012) A drought resistance-promoting microbiome is selected by root system under desert farming. PLoS One 7(10):e48479

Neilson JW, Califf K, Cardona C, Copeland A, Van Treuren W, Josephson KL, Knight R, Gilbert JA, Quade J, Caporaso JG, Maier RM (2017) Significant impacts of increasing aridity on the arid soil microbiome. MSystems 2(3):e00195–e00116

Noy-Meir I (1973) Desert ecosystems: environment and producers. Annu Rev Ecol Syst 4(1):25–51

Ortiz M, Bosch J, Coclet C, Johnson J, Lebre P, Salawu-Rotimi A, Vikram S, Makhalanyane T, Cowan D (2020) Microbial nitrogen cycling in Antarctic soils. Microorganisms 8(9):1442

Ortiz M, Leung PM, Shelley G, Jirapanjawat T, Nauer PA, Von Goethem MW, Bay SK, Islam ZF, Jordaan K, Vikram M, Hogg ID, Makhalanyane TP, Chown SL, Grinter R, Cowan DA, Greening C (2021) Multiple energy sources and metabolic strategies sustain microbial diversity in Antarctic desert soils. Proc Nat Acad Sci USA 118:e2025322118

Pointing, S.B. and Belnap, J. (2012) Microbial colonization and controls in dryland systems. Nature Reviews Microbiology 10(8):551–562

Pointing SB, Belnap J (2014) Disturbance to desert soil ecosystems contributes to dust-mediated impacts at regional scales. Biodivers Conserv 23(7):1659–1667

Qi J, Liu Y, Wang Z, Zhao L, Zhang W, Wang Y, Li X (2021) Variations in microbial functional potential associated with phosphorus and sulfur cycling in biological soil crusts of different ages at the Tengger Desert. China Applied Soil Ecology 165:104022

Salawu-Rotimi A, Lebre PH, Vos HC, Fister W, Kuhn N, Eckardt F, Cowan DA (2021) Gone with the wind: microbial communities associated with dust from emissive farmlands. Microb Ecol 82:859–869

Schulze-Makuch D, Wagner D, Kounaves SP, Mangelsdorf K, Devine KG, de Vera JP, Schmitt-Kopplin P, Grossart HP, Parro V, Kaupenjohann M et al (2018) Transitory microbial habitat in the hyperarid Atacama Desert. Proc Natl Acad Sci 115(11):2670–2675

Scott RF (1907) The voyage of the discovery, vol 1. Charles Scribner's Sons, New York

Šikoparija B (2020) Desert dust has a notable impact on aerobiological measurements in Europe. Aeolian Res 47:100636

Treseder KK, Balser TC, Bradford MA, Brodie EL, Dubinsky EA, Eviner VT, Hofmockel KS, Lennon JT, Levine UY, MacGregor BJ, Pett-Ridge J (2012) Integrating microbial ecology into ecosystem models: challenges and priorities. Biogeochemistry 109(1):7–18

Tucker C, Antoninka A, Day N, Poff B, Reed S (2020) Biological soil crust salvage for dryland restoration: an opportunity for natural resource restoration. Restor Ecol 28:S9–S16

Zhang X, Zhao L, Tong DQ, Wu G, Dan M, Teng B (2016) A systematic review of global desert dust and associated human health effects. Atmos 7(12):158

Zhang XC, Li JY, Liu JL, Yuan CX, Li YN, Liu BR, Yan XF (2021) Temporal shifts in cyanobacterial diversity and their relationships to different types of biological soil crust in the southeastern Tengger Desert. Rhizosphere 17:100322