# Arid ecosystem: future option for carbon sinks using microbial community intelligence

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*Desert, comprising one-third of the Earth's surface, was a synonym for 'no life' as it supports very less or no life due to nutritional stress and extreme weather. Microbial autotrophic biochemistry is the principal source of carbon in arid environment, but understanding of these processes in arid ecosystem is limited. Emerging molecular tools have identified associations of phototrophic and chemolithoautotrophic communities often termed as 'biological soil crust' or 'microbiotic crust'. They are the sole sources of carbon and nitrogen, collectively providing soil stability to support vegetation. Here the curiosity arises, whether this phenomenon could be exploited in deserts for carbon sink using microbial community intelligence. By following the precipitation event under regulated nutrient supply that promotes the soil microbial intelligence for autotrophy would enrich soil carbon and nitrogen which in turn support plant growth in desert. Additionally, bioaugmentation of rhizobacteria could enhance the process. This will enable us to refine and formulate our strategies to exploit $CO_2$-fixing microorganisms in such niches vis-à-vis supporting the carbon sink using microbial community intelligence.*

**Keywords:** Arid ecosystem, biological soil crust, carbon sequestration, metagenome, microbial intelligence,

CLIMATE change is a global phenomenon shown to be related with the increase of $CO_2$ levels, which have been reported up to 399 ppm in May 2013 (Mauna Loa Obser-vatoy, Hawaii). It is attracting the attention of the scientific community and correlations have shown that the increasing levels of $CO_2$ are directly associated with climate change effects[1]. There is a need to identify $CO_2$ sink options that could address the issue of ever increasing atmosphere $CO_2$ at global level. Is there an answer for this issue by increasing carbon sequestration capacity through degraded land or deserts? Deserts are a major portion of the terrestrial ecosystem, mostly considered as barren or without life due to extreme environment with unbalanced or compromised nutritional status[2]. Soils after a precipitation event, show subsurface soil heterotrophic activity. Deserts are oligotrophic in nature, here microbial autotrophy drives $CO_2$ fixation and significantly contributes to associated biomass at comparatively low levels than plants. Microbial $CO_2$ assimilation involves phototrophs and chemolithoautotrophs, viz. iron oxidizing, sulfur oxidizing, ammonia oxidizing and nitrifying bacteria. They are the key source of soil carbon in case of arid soil, principally sequestering $CO_2$ by Calvin–Benson–Bassham (CBB) cycle. Beyond the CBB cycle, there are five other options, viz. reductive acetyl CoA pathway (rACoA), reductive tricarboxylic acid (rTCA) cycle, 3-hydroxypropionate bicycle (3-HP), hydroxypropionate/hydroxybutyrate cycle and dicarboxylate-hydroxybutyrate cycle[3] available for the microbial community to assimilate $CO_2$.

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## Arid ecosystem: a future option for carbon sinks

Increasing the capacity of desert and degraded land could be the next option to sequester carbon. Long-term storage of carbon in basic resources of an ecosystem is called carbon sequestration. The two major natural C sink options are ocean and terrestrial ecosystem, of which oceans can bring maximum carbon sinks since they make 71% of the Earth's surface. Terrestrial storage includes abstraction of $CO_2$ in both forest area as well as non-forest area like desert.

### *Forest*

Forest ecosystem is a reservoir for more than 70% of the terrestrial and soil organic carbon[4,5]. Although forest floors accumulate C quickly, but being labile and available for a limited period, they are not considered as long-term solutions[6]. The potential of enhancing C sequestration rates of existing forests is not encouraging and provides a rather conflicting set of evidences[5]. Forest soils act as potential C sinks, but only a small proportion of plant-derived C becomes stabilized on the mineral soil[7]. Afforestation cannot help achieve large amounts of C sequestration than is possible by fertilization of forest, particularly on nutrient-limited sites like deserts[8].

### *Desert*

Desert covers substantial part of terrestrial ecosystem and have been shown to absorb around 100 g C/m$^2$/yr (ref. 9). The net $CO_2$ exchange data using eddy covariance method in Mojave and Gurbantunggut desert (China) suggests that deserts act as 'large carbon sink'[9–11]. However, the absolute size of desert makes it significantly more important for $CO_2$ sinks. The carbon flux between the desert soil and the atmosphere is smaller in comparison to that which takes place between organically rich soils. The carbon storage capacities of ecosystems with low organic content, viz. arid and semiarid regions are not well studied[10].

## Microbial community knowledge in deserts

Microbial autotrophs are closely associated with life on Earth and are distributed amongst all the three domains of life[3]. Microbial activity in desert soils is principally governed by soil carbon comparable to nitrogen[12]. The total organic carbon of desert ecosystem has been reported between 560 and 765 μg/g soil in Atacama Desert, whereas it is 7000 and 1700 μg/g soil in Mojave and Sahara deserts respectively[13]. The same argument strongly proposes to make the desert a better sink for $CO_2$, since a lot of autotrophic and oligotrophic bacteria are found to exist in low organics[14,15]. Though deprived of green cover, desert provides shelter to photoautotrophic and chemolithoautotrophic microbial communities that access carbon from the atmosphere[16,17]. The unvegetated soil of Atacama Desert supports many chemolithotrophic genera which were phylogenetically affiliated to previously reported non-phototrophic genera, viz. *Nitrospira*, and gamma-proteobacteria[18] that obtain energy for $CO_2$ fixation by the oxidation of nitrite, carbon monoxide, iron or sulfur. Microbial community in arid soil was also found to be rich in archaeal members affiliated to Crenarchaea[19,20], an indicator group for the operation of 3-hydroxypropionate pathway[21] and primordial life-forms. Freeman *et al.*[22] report the abundance of photoautotrophic microbial community in barren soil due to light-driven $CO_2$ influx. This $CO_2$ influx resulted in the abundance of photoautotrophic microbial communities on surface soil compared to deeper soil. Yuan *et al.*[16] determined the diversity and abundance of $CO_2$-fixing bacteria and algae by clone library, T-RFLP and qPCR of rubisco gene. The $^{14}C$–$CO_2$ incubation studies revealed the incorporation of $^{14}C$ into the soil microbial biomass accounting up to 4% of the total $CO_2$ fixed by terrestrial ecosystems per year. Yousuf *et al.*[32] studied the diversity and abundance of chemolithotrophic bacteria in coastal saline soil of Gujarat, targeting both phylogenetic and functional gene (*cbb*) marker.

Biological soil crust (BSC) is a vital C sink in the desert due to the photosynthetic community which is decisive for carbon cycling either by oxygenic or anoxygenic phototrophy[23]. The association of cyanobacteria, lichens and mosses forms the principal component of BSC[11]. It sequesters 6% of total carbon sequestered by terrestrial vegetation and fixes about 40% of biological nitrogen[24]. The crust significantly contributes soil carbon, nitrogen, nutrients and reduces soil erosion, thereby improving soil fertility[25–27]. The carbon fixation capacities of BSC increase from 0.4 to 3.3 g C m$^{-2}$ yr$^{-1}$ with its maturity as a result of increase in crust cover, its thickness, chlorophyll content, organic carbon and nitrogen content[28]. During the process of BSC succession, the cyanobacteria–algae-dominated crust shifts toward lichen–moss dominance. This shift causes increase in the amount of carbon sequestered from 11.36 to 26.75 g C m$^{-2}$ yr$^{-1}$, possibly due to more surface area and water-holding capacity of the later successions[29]. The average rate of nitrogen fixed by BSC in different deserts accounts for 70 μmol m$^{-2}$ h$^{-1}$ of nitrogen[26]. Establishment of BSC in desert supports plantation better compared to bare soil, but principally depends on the succession stage of BSC[30]. The promising route for restoration of degraded land is the establishment of BSC on dry land that results in an increase in soil organic carbon and nitrogen[28].

In desert, microbial community intelligence for autotrophy is possessed by members of cyanobacteria, chloroflexi, bacteroidetes/chlorobi and some proteobacteria[16,31,32] along with group chemolithotroph affiliated with purple sulfur, purple non-sulfur, green sulfur and green non-sulfur bacteria. Besides the knowledge of autotrophy, understanding of nitrogen fixation by *Azospirillum* sp., *Rhizobium* sp. and *Pseudomonas* sp. is also present in arid ecosystem[33]. It is proposed that if the intelligence for carbon, nitrogen and nutrient cycle possessed by microbial components of BSC could be harnessed for increasing the soil nutritional status, then a system with enhanced efficiency of carbon sequestration could be designed (Figure 1). So the key to account desert as a carbon sink should be to consider together the effect of precipitation event, temperature, soil process and microbial activity to support plant productivity[34].

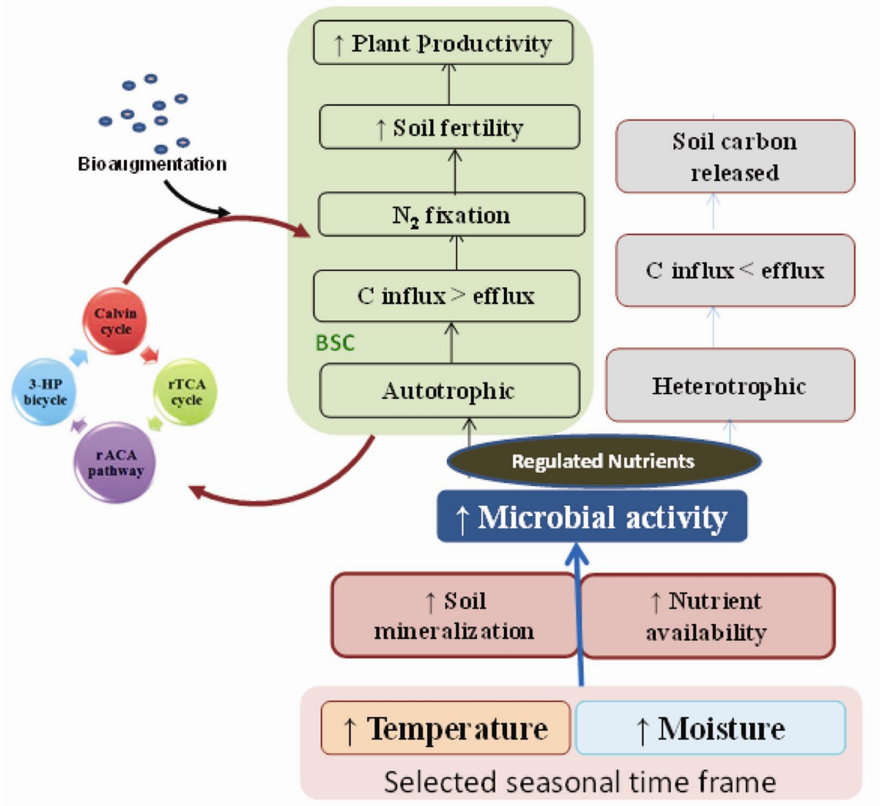


**Figure 1.** Conceptual strategy for carbon sequestration in arid ecosystem using microbial community intelligence: The identification of critical time-frame for precipitation event and its exploitation in favour of development of effective biological crust (BSC) has been hypothesized. It includes defining the strategy for development of microbial community intelligence for carbon sequestration by identification of community structure or by applying required microbial members to complete the desired community structure. This could be further assisted by supplementation of nutrients responsible for synthesis and stabilization of BSC under the selected climatic conditions of temperature and humidity. Establishment of such microbial knowledge would ultimately support in an increase of soil carbon, nitrogen and its fertility. The programmed scenario would support the pool of nutrients to heterotrophs and plant to further participate in sequestration process. Conversely, under non-optimal climatic conditions of increased temperature and humidity, deep subsurface heterotrophic microbial activity enhances, which further reduces soil carbon resulting in land degradation.

## Molecular tools aiding mining the microbial community intelligence

Microbial community intelligence is the overall knowledge that a community has in order to adapt to the present state of stress or environmental conditions by altruistic or cooperative behaviour. Such example of microbial community intelligence is found in soil ecosystems. Soil is a complex dynamic biological system that harbours almost 4000 different bacterial species/g soil, but almost 99% could not be isolated due to unavailability of the knowledge about their culturing conditions. This 99% could be accessed by metagenomics, which provides the knowledge of total community from any environmental sample. It is an efficient technique to address the functional capacity of uncultivable microorganisms from any niche[35]. The advancement of soil metagenomics provides a new perspective for understanding the role of soil microorganisms and to unearth the hidden functional knowledge associated with the microbial community, even with the extreme environment like Atacama Desert[2,36,37]. Earlier studies on the microbiology of desert soil have proved that life in the desert was not explored due to limitations of culturing techniques. The emerging molecular tools could be applied for the analysis of microbial wealth while considering the possible limitations[16,38–40]. Improvement in DNA extraction efficiency and high sampling frequency is required to explore the huge microbial world, inhabiting the soil[39]; and this could be further improved using high throughput approaches such as microarray[41,42].

Next-generation sequencing techniques have opened a wide spectrum of taxonomic and functional aspects of microbial community[43]. Identification of many unculturable microbes and archaeal members of group Thermoprotei in Sonaron Desert soil highlights the magnitude of pyrosequencing[12]. Of late, metatranscriptomics and metaproteomics have been evolved to access the functional knowledge from such a vast metagenome data[43]. The functional annotation of such datasets is based on homology search against the publicly available database and requires knowledge of bioinformatics tools and computational storage space[44]. Recent advances in the field of microbiology, biotechnology, molecular biology and bioinformatics opened up the way to identify novel genes and for improving the quality of target output[45]. There are many microbes reported for $CO_2$ fixation through unknown pathways, pointing towards the scope of finding new genes, enzymes and pathways underlying $CO_2$ fixation[46]. Developing such resource and database enlightens the area of research and the understanding of new genes and pathways.

The biochemistry of $CO_2$ fixation by microbial communities in extreme environments could be understood by exploring the genetic information carried by the metagenomes. Metagenome analysis suggests colonization of various phototrophs and lithotrophs in Arctic, Antarctic and Atacama Desert[2,25,37,47]. This was evidenced by the identification of *rubisco* gene in the metagenome[32,48]. Marker genes for $CO_2$ fixation were observed in metagenome isolated from various niches, but little is known about the $CO_2$ fixing gene other than *rubisco*. Hence there is still scope for finding new genes that can fix $CO_2$ in arid ecosystems. In addition to the phylogenetic analysis, knowledge of functional gene diversity is more important to study climate change impact in desert and provide insight into the role of desert as a $CO_2$ sink.

## Community response to climatic drivers

The Southeast Asian region is observing the shift in the geographical distribution of rainfall pattern. The trend shows that it is moving towards the western plains and feeding the precipitation to deserts and also moving towards the Middle East[49]. Desert is highly responsive to climatic variability since bacteria-inhabiting deserts are under various stresses, viz. temperature, salinity, precipitation, carbon, etc. The bacteria that survive in desert cope with these stresses. The presence of carbon dioxide-fixing bacteria in deserts counteracts the carbon stress by fixing the inorganic carbon and hence increases soil organics and supports other lifeforms. The member of genus *Azospirillum,* a known plant growth promoting bacteria (PGPB), exerts its growth-promoting effect on plants under various desert stresses of salinity[50], drought[51] and extreme pH[52]. The soil microbial community alters with change in precipitation, atmospheric $CO_2$ concentration and temperature[53,54]. In arid ecosystems, precipitation is the key driver controlling carbon, nitrogen and nutrients due to change in microbial response[55]. The nature of episodic precipitation events in arid ecosystem increases carbon influx due to increased surface microbial autotrophic activity. The soil of Kalahari (Botswana) Desert harbours cyanobacteria, which fix atmospheric $CO_2$ to add significant quantity of organic matter[56]. The gains and losses of $CO_2$ through the sands of Kalahari Desert after light rainfall are the same as grassland soil, but after the heavy rainfall, large amount of $CO_2$ is released due to increased degradation of organic matter by heterotrophic bacteria, which masks the activity of cyanobacteria. The heterotrophic microbial respiration operates at a very low level in the desert ecosystem and for short durations, particularly after rains, when the availability of nutrients enables $CO_2$ efflux[55]. In response to the increased precipitation in desert soil, the rate of carbon efflux is observed in the range 65.6–339.2 mg C $m^2$ $h^{-1}$ compared to 2.8–14.8 mg C $m^2$ $h^{-1}$ in dry soil[56]. $CO_2$ efflux increases with an increase in soil temperature due to more heterotrophic microbial activity[57]. As increase in soil temperature limits moisture and results in reduced $CO_2$ fixation capacity of desert due to declined phototrophic activity. Here the microbial intelligence and natural selection favours the temperature-tolerating phototrophic members in order to provide soil stability[58].

Another climatic driver is atmospheric $CO_2$ concentration, which is ever-increasing since 1988. Elevated $CO_2$ concentration causes an increase in soil carbon sequestration due to increased plant productivity[59]. The soil enzyme activity alters in response to elevated $CO_2$ that affects the quantity and quality of soil organic matter and microbial processes[60]. Microbial response to such an elevated $CO_2$ was studied in different ecosystems, but the observation suggests the need for more extensive analysis to reveal the microbial response to these changes[61]. An integrated approach of pyrosequencing and GeoChip has suggested that the functional structure of soil community alters under elevated $CO_2$ (ref. 42). There was an increased abundance of genes responsible for carbon fixation, nitrogen fixation and phosphorus release under elevated $CO_2$ (ref. 42). A variety of carbon sources and their metabolites support the network of different genomes, which collectively decide the way a biological process evolves under the stress conditions prevailing in such a system[62].

## Instances of microbial community intelligence exploitation

Increasing the capacity of desert and degraded lands could be the option to sequester carbon vis-à-vis $CO_2$ mitigation. Integrating various approaches of carbon sequestration and energy generation, exploiting microbial intelligence could serve as a better option in the near future. One such paradigm is a Sahara forest project, which aims at integrating different technologies where processes feed each other and provide environmental as well as commercial benefits. This serves turning an arid land into green oasis[63]. Another project 'Biodesert program' enables unearthing of microbial resources in deserts, which serve as a knowledge pool to develop approaches to mitigate climate change. Carbon cycling is one of the thrust research areas of the Genomic Science Program funded by US Department of Energy (DOE) (http://genomicscience.energy.gov/). It is aimed at developing biosequestration strategies for ocean and terrestrial ecosystem. The DOE Joint Genome Institute has generated genome sequences of many microbes and plants, which provide knowledge of microbial/microbial community intelligence. Genomic science researchers are developing advanced methods to translate microbial intelligence into an understanding of function to provide insights into plant–microbe and microbe–microbe interactions that increase carbon fixation in soils. Synthetic biology has come up to explore microbial intelligence of stress survival for smart assembly of genome 'parts' to find key solutions to carbon sequestration and climate change[64]. Such resources fulfil the DOE mission of synthesizing a microbial system that was otherwise unculturable, to improve carbon fixation capacities in soil and sediments. Application of bioaugmentation strategy could also enhance the process of carbon fixation in arid systems. Rhizospheric plant–microbe interaction serves as one of the options to enhance carbon sequestration[65]. It enhances nutrient uptake capacity of the plant due to increase in surface area of roots, nitrogen and phosphorus availability. Researches targeting the development of microbial consortia involving microbial members responsible for nitrogen fixation, phosphorus solubilization, siderophore production, phytohormone synthesis, biological crust formation that would finally support plant growth in symbiotic or non-symbiotic manner could help develop microbe-based strategies for carbon sequestration. Restoration of Sonoran Desert has been demonstrated by bioaugmentation of PGPB formulation consisting of *Azospirillum brasilense* and *Bacillus pumilus*, along with arbuscular mycorrhizal fungi and compost[66,67]. However, the plant growth response depends on the varying degrees of bio-formulation application. A bio-formulation of immobilized *A. brasilense* and microalgae *Chlorella sorokiniana* was also used to increase the organic content of desert soil to support sorghum plantation[68]. By integrating the knowledge-based research of application of PGPB with the development of application-based technology would promote desert farming. This basically relies on the detailed knowledge in terms of soil characteristics, climatic factors and microbial intelligence present in that niche that has to be reclaimed. This enables us to understand the missing knowledge that could be offered externally favouring the natural entropy. The microbial community reserves of an arid ecosystem may offer insight into finding new solutions to global environmental issues and adding up to the existing natural capacities.

## Conclusion

Deserts can be equated as dry 'oceans', but the vision of converting deserts into green oasis could address the problem of climate change. A biological approach for carbon capture through the microbial process in deserts is the establishment of BSC. Researches targeting to identify the factors promoting BSC formation and their effect on plant establishment offer a way to develop desert as a carbon sink. Additionally, bioaugmentation of PGPB could also address soil fertility. The genetic potential to fix $CO_2$ is widespread in soils; their capacity to fix $CO_2$ has yet to be fully investigated. The knowledge of key functions related to climatic drivers, their effect and microbial responses within the desert ecosystem would be useful for developing better solutions for carbon sequestration in the desert.


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ACKNOWLEDGEMENTS. L.A. thanks the Council of Scientific and Industrial Research (CSIR), New Delhi for the award of Senior Research Fellowship. R.N.S. is grateful to INSA for the award of Senior Scientist Scheme. We thank the Directors of CSIR-National Environmental Engineering Research Institute, Nagpur and CSIR-Institute of Genomics and Integrative Biology, Delhi, CSIR-WUM (ESC0108) for providing the necessary funds and facilities.

Received 2 January 2014; revised accepted 21 March 2014