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Forum

Engineering carbon sequestration on arid lands

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To limit the effects of global warming, arid lands, which constitute approximately one-third of terrestrial surfaces and are not utilized for agriculture, could serve as an effective method for long-term carbon (C) storage. We propose that soil–plant–microbiome engineering with oxalogenic plants and oxalotrophic microbes could facilitate C sequestration on a global scale.

With greenhouse gas (GHG) concentrations at the highest level for 2 million years, humanity is facing an unprecedented challenge from climate change [1]. Consequently, average temperature increases, ice sheet melting, ocean/sea level increases, and extreme weather patterns are becoming routine. These changes threaten the foundations of human civilization.

Net CO_2 emissions have to be reduced to zero within 10 years to achieve climate neutrality [1], but climate effects of elevated atmospheric CO_2 will remain irreversible for at least 1000 years unless CO_2can be sequestered from the atmosphere [2].

The global C cycle includes the atmosphere, marine, and terrestrial ecosystems (Figure 1). Overall, terrestrial and aquatic net primary production and assimilation are nearly balanced, but human activities perturb the global C cycle, leading to an approximate 5.2 Gt (gigatonnes) C increase in atmospheric CO_2 per year [3] (Figure 1). All paths toward the 1.5°C goal depend on a rapid reduction of the C footprint of agriculture, forestry, and land use, combined with the enhanced use of bioenergy for C capture and storage [4,5].

Mitigation strategies to reduce GHGs in the atmosphere

Among the various approaches to reduce atmospheric GHGs, reforestation is a frequently discussed strategy for C sequestration. Trees are considered an ideal method to achieve this objective due to their natural ability to capture CO_2 through photosynthesis, converting it into biomass that can store C for extended periods of time. However, reforestation usually targets land that competes directly with food production and many natural forests were lost in recent years due to the conversion of forests to agricultural land. By contrast, one-third of the terrestrial surface of our planet is arid land that is not used for agriculture and is subject to significant degradation. A number of large reforestation projects have been launched in recent years to reclaim arid regions. So far, the potential of replanting arid lands for C capture has been overlooked. We propose here that reforestation of arid lands by appropriate ecosystem engineering would not only bring back barely covered lands to vegetation but might also provide ideal sites for C sequestration. The advantage of reclaiming arid regions for regreening and C sequestration is that they do not compete with lands used in agriculture and food production.

The terrestrial C cycle and C stocks

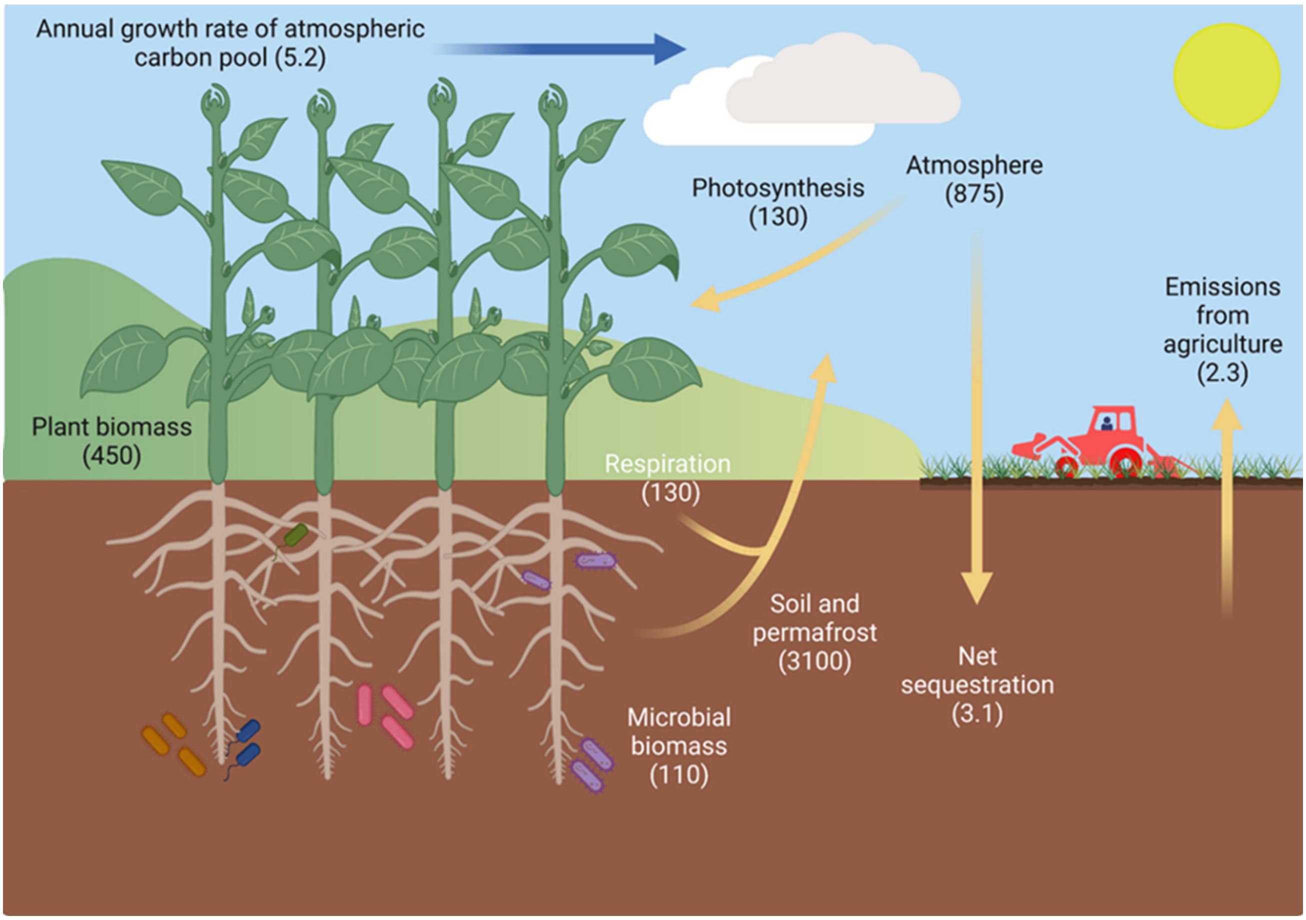
C is mostly found in the lithosphere (66–100 million Gt (gigatonnes) C), oceans (38–40 000 Gt C), soil (3100 Gt C), atmosphere (875 Gt C), and the biosphere (450 Gt C). Natural terrestrial C sequestration entails capturing atmospheric CO_2 by vegetation, before transporting a significant amount of C to the soil which acts as the largest terrestrial C sink (Figure 1) [6]. Soil C (3100 Gt C) comprises both soil organic carbon (SOC) as 1500–1600 Gt C and soil inorganic carbon (SIC) as 700–1700 Gt C and largely contributes to total terrestrial C stocks. Soil C is, however, not static but undergoes dynamic changes influenced by temperature, atmospheric CO_2 concentrations, land use, and soil management practices [6]. In contrast to soil C (3100 Gt C), vegetation (450 Gt C) holds much smaller amounts of C.

SIC formation and arid lands

C stocks of arid lands make up about one-third of global soil C and most of these are not in the form of SOC, which is poorly present in arid soils. The reasons for this are the sandy soil character, extreme temperatures, and the sparsity of vegetation (the main producer of organic materials). By contrast, arid soils are rich in SIC, mostly in the form of calcium carbonate ($CaCO_{3)}$, which can form under specific conditions: soil must be alkaline (high pH), rich in calcium ions (Ca^{2+}), have low soil moisture, and must have an active source of bicarbonate (HCO_3^-).

SIC formation can naturally occur by abiotic mechanisms when dissolved $CaCO_3$ crystallizes under low soil water content or biotic means when soil microbes produce carbonates via the oxalate carbon pathway (OCS), which can precipitate as $CaCO_3$ in the presence of high Ca^{2+} concentrations in the soil [7].

SOC and SIC are contrary in occurrence and behavior. Whereas SOC is mostly found in the top layer of humid soils of forests and grasslands, with very low SIC levels, SIC is mostly found in arid and hyper-arid soils and not only in top soil but also down to depths of several meters [8]. SIC is considerably more stable than SOC and can persist for hundreds to thousands of years in soil under optimal conditions, but is also affected



Trends in Plant Science

Figure 1. Schematic representation of the terrestrial carbon (C) cycle. Annual growth rate of atmospheric C pools (blue arrow) is the differential of emissions from fossil fuels (9.6 Gt C), land use change (1.2 Gt C), and uptake of C into terrestrial (3.1 Gt C) and oceanic (2.9 Gt C) C pools. Only land-based C fluxes are shown here [10]. Abbreviation: Gt, gigatonne.

by changes in climate, weather, land use, and farming [8].

Plant adaptations to arid lands – oxalogenic plants

To engineer SIC formation for C sequestration, it is essential to understand the soil–plant–microbe holobiont system of soil carbonate formation. The first layer of this system is the plants that fix atmospheric CO_2 through photosynthesis. This process is driven by the photochemical conversion of CO_2 and H_2O into carbohydrates. Plants then convert carbohydrates further into other substances and use these as energy sources and building blocks to manufacture the most amazing complex structures, such as beautiful flowers, bushes, or meter-high trees. In arid lands, the limiting factor for plants usually is neither sunlight nor CO_2 but the availability of water, which limits growth and vegetation cover. However, arid land-adapted plants, called xerophytes, have evolved their morphology, architecture, and metabolism to dry conditions [9,10]. In addition to short-lived annual xerophytes, adapted perennial shrubs and trees can withstand long periods of drought due to their ability to reduce transpiration and evaporation [11]. Some xerophytic shrubs and trees have adapted their root architecture to develop taproots that reach dozens of meters into the soil in the search for water [9]. The modification of root morphology and root components such as suberin in crops has been suggested as a strategy to enhance soil C content [12]. However, the generation and large-scale deployment of such crops might take considerable time to reconcile soil effects, yield efficiency, and crop quality with such genetic engineering. In arid regions, many plants have adapted their photosynthetic metabolism to the C4 or crassulacean acid metabolism (CAM) mode [9]. C4 plants store photosynthetically-derived malate in mesophyll cells before conversion to pyruvate and CO_2 in bundle sheet cells. CO_2 is therefore generated without any gas exchange and water loss during the hottest part of the day. CAM plants, such as cacti, close their stomata during the day and use photosynthetically-derived malate during the night with minimal transpiration losses to feed the Calvin cycle. A much less known specifically adapted metabolism in many plants of arid regions is the use of the OCS. Using this pathway, plants store carbohydrates as metabolic water in the form of calcium oxalate crystals, which can be converted to H_2O and CO_2 during periods of drought [13]. These plants are called oxalogenic species and are widely distributed in arid regions.

Microbial adaptations to arid land conditions – oxalotrophs

All plants secrete one in every four fixed Cs into the soil to feed a microbial world of organisms. It is in this aspect that arid soils differ strongly from non-arid soils in showing a large number of specialized microbes, called oxalotrophs, which can use the plant-derived oxalate as an exclusive C source [13]. The microbes, which proliferate on oxalate, use the C atoms for their own metabolism, but one in every four Cs derived from oxalate is secreted into the soil as carbonate by the oxalotrophic microbes [13]. Carbonates are not stable molecules and are rapidly converted to H_2O and CO_2 in acid and humid soils, explaining the sparsity of carbonates in these soils. However, under alkaline conditions and in the presence of Ca^{2+}, typical conditions of arid lands, the carbonate molecules can precipitate as $CaCO_3$. This process can occur not only in the biome-rich top soil but also in deeper soil layers, explaining why massive $CaCO_3$ deposits are stable for hundreds to thousands of years. Overall, in this form of C sequestration, one out of every 16 photosynthetically fixed Cs might be sequestered into carbonates.

Engineering C sequestration on arid lands

A combination of oxalogenic plants with oxalotrophic microbes forms part of the system to establish C sequestration in arid lands. However, the system is complicated and one has to consider the particularities of the respective soils. Soils of arid lands usually not only have a poor texture with a low water-holding capacity but high pH also contributes to their poor nutrient bioavailability, so that many plants are unable to retrieve nutrients from and grow on these soils [9]. In addition to the availability of water, these conditions constrain the growth, proliferation, size, and density of vegetation in arid regions and contain a variety of specialized microbes to overcome these limitations. These microbes live in association with arid land plants and can fix nitrogen and help retrieve phosphate, iron, and other nutrients and minerals from the soil [10]. However, using artificial intelligence (AI)-based knowledge of the particular soil–plant–microbe system can allow definition of the optimal combination of oxalogenic plants, oxalotrophic microbes, and soil type for carbonate sequestration (Figure 2). In this way, engineering the soil–plant–microbe holobiont system could become a promising method for C sequestration in the near future.

For any C sequestration technology, an essential point is the proportion of arid lands that would be suitable [14]. Globally, most arid regions share similar soil properties with regard to carbonate content, but since the proposed oxalogenic strategy is based on the use of selected plant–microbiota combinations, ecological restoration principals adapted to arid ecosystems should be best used. Regreening deserts by restoration of ecosystem functions, including C sequestration, should be the preferential approach. Here, fertility islands could be starting points for the

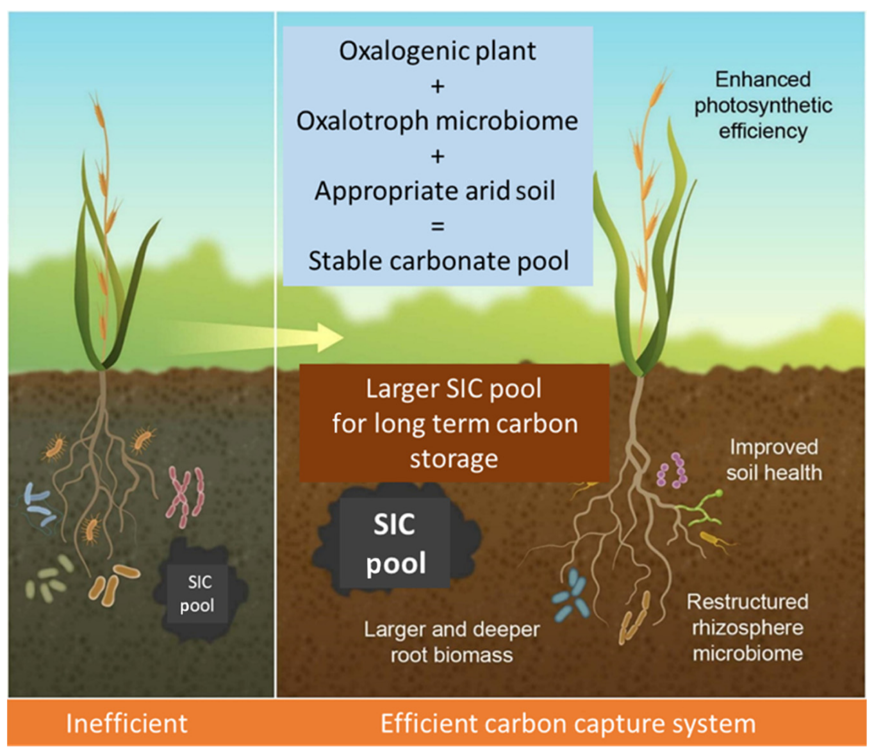


Figure 2. Engineering soil–plant–microbe systems for carbon sequestration on arid lands. To advance from the current inefficient to an efficient carbon capture system, the best combination of oxalogenic plants and oxalotrophic microbes has to be paired with arid calciferous soil systems of high pH. Abbreviation: SIC, soil inorganic carbon.

recolonization of the ecosystems and spread of the biodiversity could be achieved with minimum energy input.

To estimate the time span needed for the proposed oxalogenic approach to make a significant impact on C sequestration will not only depend on the limited growth of plants due to water scarcity in arid regions. Coupling the oxalogenic process to ecological restoration based on fertility island approaches and ecological engineering techniques can achieve significant increases in both plant and soil C sequestration within a relatively short period (<10 years) but will also depend on the financial and political means to apply this technology in various arid countries.

Declaration of interests

No interests are declared.

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