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News & Focus

Desert "Soilization": An Eco-Mechanical Solution to Desertification

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Desertification refers to the degradation of land [1–4]. As a severe global environmental problem, it has drawn considerable attention from the international community. *The United Nations Convention to Combat Desertification* [4] was adopted by the United Nations in 1994, and since that time, countries around the world have made ever-increasing efforts to combat desertification [5–12]. However, the spread of desertification has not been controlled. Instead, it is becoming even worse; it is expanding at a rate of 50 000–70 000 km^2 annually [13,14]. At present, desert and other dryland regions endangered by global desertification account for 41.3% of Earth's land area [2,15–17]. In China, the desertified land is approximately 1.73×10^6 km^2 which is 18.03% of the national territory, and another 3.1×10^5 km^2 is tending to be desertified [18].

Desert control poses a global challenge. Presently, there exist three prevailing types of methods of desert control [1,9–12,19]: engineering methods, chemical methods, and vegetation methods. These methods have all played a positive role in desert control. The principle of engineering methods is to prevent the drifting of sand by building barriers, such as straw checkerboard barriers and sand fences. Chemical methods involve spraying oil, bitumen or latex onto the surface of sand to cause the surface layer to solidify. In vegetation methods, sand is usually remediated through the planting of psammophytes. However, none of the above methods is capable of changing the material characteristics of sand into those of soil.

The proposition of desert "soilization" is based on the realization of sand "soilization," which presents a promising alternative to the prevailing methods of desert control. Sand "soilization," i.e., the turning of sand into "soil," is a remarkable transformation based on the revelation of the eco-mechanical attributes of soil. It has been found by Yi et al. [20] that the mechanical properties and ecological attributes of soil are closely correlated. Soil is in a rheological state when wet and in a solid state when dry, and it can readily transform between these two states. These mechanical properties of soil endow it with the two eco-mechanical attributes of self-repair and self-regulation. An analysis by Yi et al. [20] has shown that these two attributes are the prerequisites for soil to maintain its endless eco-cycle and to serve as an ideal habitat for plants. If these two attributes are lost, then the soil will degrade, and one of two scenarios may emerge: soil hardening or soil desertification. Based on the above finding, sand "soilization" has been achieved by Yi et al. by imposing an appropriate constraint among the sand granules.

Sand, as it is defined in geology or engineering [19,21], exists in a discrete state, and the constraint that acts among its granules is a contact constraint. When a suitable water-based paste is added to and mixed with sand granules, then an omni-directional integrative (ODI) constraint (with omni-directionality and restorability) will form among the granules instead, and the sand will be transformed into a rheological state (wet "soil") [20]. After the evaporation of the water content in the paste, the ODI constraint will transition into a fixed constraint, and the sand will transform into a solid state (dry "soil"). "Soilized" sand possesses the mechanical properties of natural soil, which can continuously transform between the rheological state and the solid state. Thus, such "soilized" sand possesses the same eco-mechanical attributes as those of soil. Because the necessary constraint is imposed on the sand granules by means of a water-soluble paste, this "soilized" sand also possesses a strong capacity to retain water, nutrients, and air. Clearly, there is no significant difference between the "soilized" sand and natural soil in terms of their mechanical properties and ecological attributes. Yi [22] has found that once sand is "soilized," it becomes suitable for the growth of plants, thus making it an ideal habitat for plants.

Since 2013, we have been conducting an outdoor planting experiment at two sites (with areas of approximately 550 m^2 and 420 m^2, respectively) in the Nan'an District of Chongqing, China. Desert landform conditions were simulated in the experiment by establishing a 15-cm- to 25-cm-thick plain sand layer underlain by a 20-cm- to 30-cm-thick gravel layer on the ground. Afterward, three types of "soilized" sand layers with thicknesses of 10–20 cm, which were obtained by mixing sand with a modified sodium carboxymethyl cellulose (CMC) solution (containing 2% modified CMC and 5% compound fertilizer) at a weight ratio of 1∶0.15, were placed on top of the plain sand layer in separate sections. Three types of commercially available sand for building and construction (clean river sand), with different fineness moduli of 1.22, 2.97, and 3.71 and without any soil content, were subjected to "soilization" for the experiment. In addition to these river sands, three other granular materials (machine-made sand from stone, sand mixed with machine-made sand from stone, and sand mixed with saw-dust) were also used in the planting experiment after "soilization." Many types of plants (Fig. 1(a)), such as rice (Fig. 1(b)), corn (Fig. 1(c)), and sweet potatoes (Fig. 1(d)), were planted in the "soilized" sand. In each year of the experiment, the

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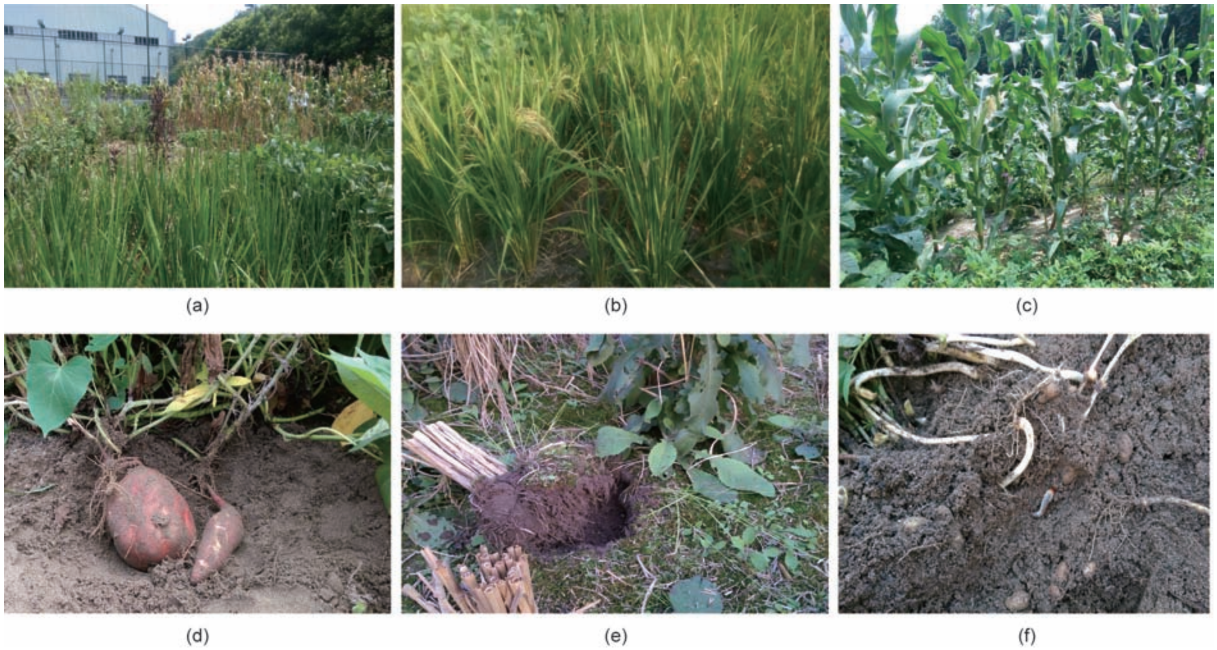

Fig. 1. "Soilized" sand: an ideal habitat for plants. (a) Various plants planted in "soilized" sand; (b) rice growing in "soilized" fine sand; (c) corn growing in "soilized" coarse sand; (d) sweet potatoes growing in "soilized" moderate-grain sand; (e) after the harvest (of rice), the "soilized" sand remained in good condition, and the algae on the surface of the "soil" demonstrated that the constraint introduced into the "soil" could not be washed away by water; (f) insect larvae appeared in "soilized" sand.

plants have survived the heavy rains and continuous high temperature over consecutive sunny days that are characteristic of the climate in Chongqing, China. During these periods of continuous high temperature, the plants have been appropriately watered at different intervals. The constraining material was added to the "soils" only once in the spring of 2013, and no further supplementation has been made to the "soils" after that, except for the addition of an appropriate amount of fertilizer each year since 2014. There have been two harvests each year, and the plants have always grown luxuriantly and fruitfully in the different "soils." In the years 2014 and 2015, the comparison of the yields of the plants including corn, potatoes, sweet potatoes, radish, and oilseed rape was made with those grown in the nearby fields of natural soil. The results show that all yields in the experiment field were higher, and in particular, the yields of three plants (potatoes, sweet potatoes, and radish) with tuber or tuberous roots were 50% higher (with the reasons and underlying mechanism to be elaborated upon in our next paper on eco-mechanics of soil). The planting experiment proves that the "soilized" sand has not turned back into its original discrete state by the erosion of rainstorm. On the contrary, the plots that were watered more frequently (for example, the plot in which rice was planted) have been found to be heavily covered with algae (Fig. 1(e)). Our planting experiment further shows that the eco-mechanical attributes of the "soilized" sand have been further improved throughout the cycle of planting and cropping, with the "soilized" sand behaving increasingly similarly to natural soil. Three months after the first harvest, organisms such as ants, earthworms, centipedes, and insect larvae had already appeared in the "soil" (Fig. 1(f)).

The planting experiment described above verifies that "soilized" sand is an ideal habitat for plants and that its eco-mechanical attributes can be retained over the long-term.

Desert "soilization," i.e., the "soilization" of the surface layer of desert sand, is an unprecedented scientific proposition. The essence of desert "soilization" is to enable surface sand to acquire the mechanical properties and ecological attributes of soil. In principle, desert "soilization" is the inverse process of desertification. Desert "soilization" has the potential to make deserts bloom, improve the ecological environment in desert regions, and, ultimately, benefit mankind.

To verify the feasibility of desert "soilization," in April 2016, we started a large-scale planting experiment in "soilized" sand in the Ulan Buh Desert, the Inner Mongolia Autonomous Region, China. Covering an area of approximately 10 000 km^2, the Ulan Buh Desert is located at approximately 1100 m above sea level. This desert is characterized by little rainfall, with an average annual precipitation of only 102.9 mm, and severe wind erosion. It is one of the most severely desertified regions in China and one of those that are most difficult to control. Our experimental field is located at 39°36′32″N, 106°39′02″E in the Ulan Buh Desert with the altitude of 1110 m above the sea level (Fig. 2). Because the underground water resources in Ulan Buh Desert are quite abundant (the reserve volume is approximately 5.7×10^9 m^3), all of the water used to convert the sand into "soil" and for the irrigation of the plants growing in it is sourced from underground water. In the experiment, the content of added constraining material, such as modified CMC, in the sand is between 0.1% and 0.4%. The desert sand and the constraining material were first mixed using a mixer and then paved onto the desert surface with an average thickness of 10 cm (Fig. 2(a)). A nitrogen-phosphorus-potassium compound fertilizer was also added at a weight ratio of 0.3% with respect to the sand. The "soilized" sand possesses a strong water retention capability (Fig. 2(b)). A spray atomization irrigation system was used in the experiment (Fig. 2(c)). In an attempt at large-scale mechanized preparation, we even used a rotary cultivator to mix the "soilized" sand and apply it over an area of 2000 m^2, and the results suggest that such a mechanized preparation approach is feasible for large-scale desert "soilization" (Fig. 2(d)). Approximately 50 different plant seeds or seedlings, including *Festuca arundinacea*, coreopsis, wheat, corn, sunflower, sand jujube tree, and poplar tree, were sowed in the experimental field (Fig. 2(e)) beginning on May 20th, 2016. At present, more than 70 kinds of plants (over 20 of which may have been introduced by wind or birds) are growing healthily and robustly in the field (Fig. 3(a)–(e)), and the growing of some algae on the "soil" indicates that a new ecological cycle different from the one common in desert is forming. Insects, such as butterflies, mosquitoes, and ants, and other animals, such as birds, mice, and even frogs are staying and living in the experimental field (those animals can rarely be seen in the desert). Sometimes foxes and badgers are also seen in the field.

For comparison with the results of the above experiment, we also planted in three plots of desert land near our experimental field. In sharp contrast to the experimental field, although the same methods of sowing, watering, and fertilization were used, the plants in these three plots of land have grown very little (Fig. 3(f)) because the sand does not possess the eco-mechanical attributes of soil and cannot resist erosion by wind.

When the content of the constraining material, i.e., modified CMC, that is added to sand reaches 1.0%, the "soilized" sand takes on an even stronger water retention capacity, becoming even as impervious as mud. To fully utilize this special property of the material, we have constructed two paddy fields (Fig. 2(f)) and are attempting to grow aquatic plants in them.

The outdoor experiment in desert has further confirmed that the "soilized" sand does serve as an ideal habitat for plant species. The experiment has also verified that the "soilized" sand shows

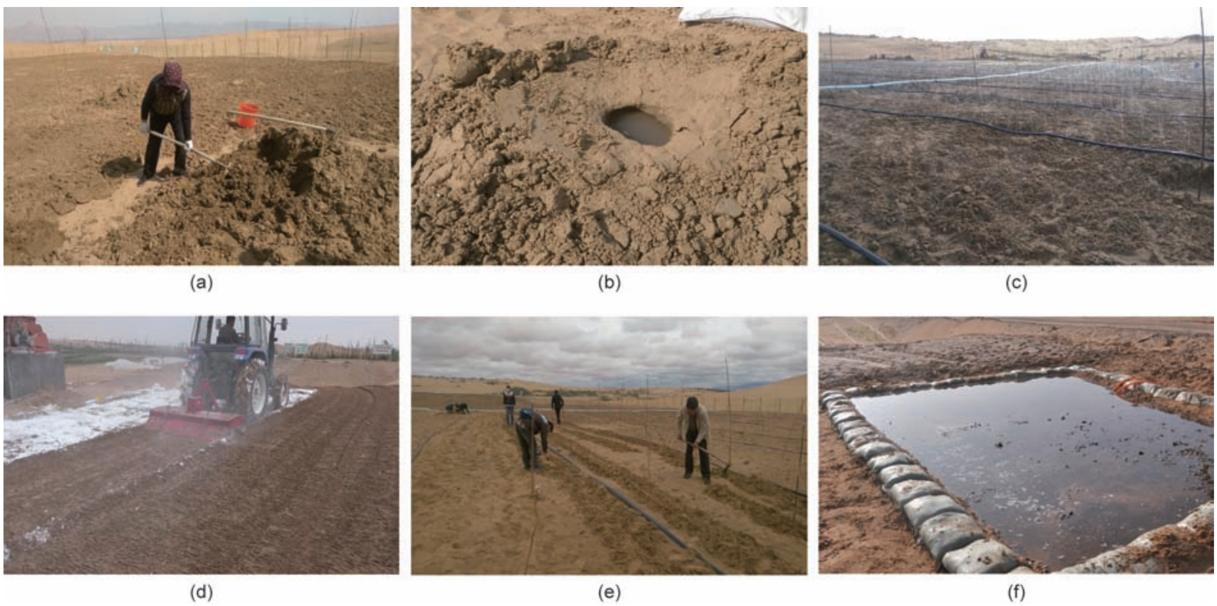

Fig. 2. "Soilized" desert sand in the Ulan Buh Desert. (a) Desert sand that has been "soilized" being paved onto the desert surface; (b) the water still retained in the 20-cm-deep hole in the "soilized" sand 24 h after it was fully filled up; (c) the spray atomization irrigation system; (d) the mechanized preparation of sand "soilization" using a rotary cultivator; (e) planting in the "soilized" sand; (f) a paddy field constructed in the "soilized" sand (walls were constructed at the edges of the field edge using bags full of "soilized" sand).

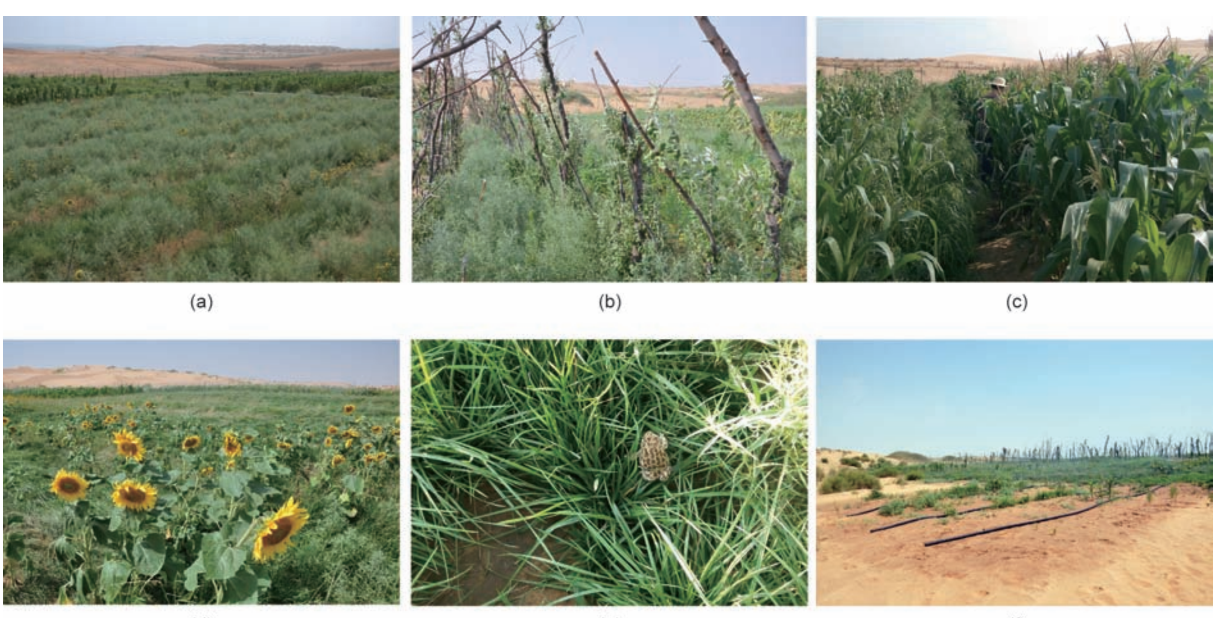

Fig. 3. Various types of plants grown in the "soilized" desert. (a) More than 70 kinds of plants grown in the "soilized" desert; (b) sand jujube trees and grass; (c) corn and proso millet; (d) sunflowers and grass; (e) a frog staying on the grass; (f) for comparison, an image of the plants grown in desert land using the same methods of sowing, watering, and fertilization as those used in the "soilized" sand.

strong resistance against wind erosion. Ulan Buh Desert is known to be a desert on the move, and worse still, our experiment field is located between two sand hills with strong wind blowing through. However, the "soilized" sand in our experiment field has successfully prevented wind erosion while the areas around have undergone apparent change due to the strong wind. The reason why the "soilized" sand is strongly resistant against wind erosion is that the "soilized" sand mass, whether it is in the rheological state when wet or in the solid state when dry, are held together by constraint, which behaves like natural soil, and there exists no discrete granules.

Based on the granular constraint principle, the method used to implement sand "soilization" is simple. The added constraining material is modified CMC (a kind of plant cellulose), which can be used as food additives, is non-toxic, environmentally friendly, cost-effective, and suitable for mass production. A small amount (as little as 1%–5%, for example) of modified CMC added to water can produce a highly viscous paste. If mechanized preparation methods such as rotary cultivation are adopted, the work involved in planting in "soilized" sand will not be much greater than that for planting in arable land. From an economical perspective, because the content of the constraining material is quite low and the preparation method is simple, the total cost for desert "soilization" is between 4500 and 6500 dollars per hectare depending on the planting requirements.

Natural soil usually takes thousands of years to form. However, by means of sand "soilization," sand can be turned into "soil" such that it instantly becomes an ideal habitat for plants. Desert "soilization," which offers a solution to various problems commonly encountered in desert control, such as sand drifting, poor water retention, and the consequent hostility to plant species, has been achieved through interdisciplinary studies combining mechanics, ecology, soil science, and phytology. We believe that the extensive implementation of desert "soilization" for desert control in the near future may foster many new disciplines and industries. Soil degradation has resulted in various global environmental problems [23–25]. The large-scale application of sand "soilization" for planting has the potential to enable the establishment of a thriving desert ecosystem, which may offer a solution to several global environmental problems, such as deforestation, bio-diversity loss, and climate change [16,26–28]. However, large-scale desert control must take into consideration the risks of excessive or undue exploitation of underground water resources [29–32], and make good preparation for the potential impacts including the regional climate and bio-diversity changes brought about by extensive desert "soilization." Therefore, before the large-scale application of desert "soilization," scientifically comprehensive planning and assessment must be carried out first, and desert "soilization" might start from areas with access to adequate water resources.

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