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An Artificial Oasis in a Deadly Desert: Practices and Enlightenments

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Abstract: Building highway and its biological protection system in a drought-affected shifting-sand desert is a great challenge. This challenge was completed by the construction of the Taklimakan Desert Highway Shelterbelt (TDHS)—the longest of its kind in the world (436 km). The TDHS can serve as a model for highway construction and desertification control using eco-friendly and cost-effective approaches in other desert regions. Notably, we proved that local saline groundwater irrigation offers potential advantages and opportunities for the growth of halophytes and sandy soil development in hyper-arid desert environments. Here, we systematically (1) summarize the project, its results, and vital technical issues of saline water irrigation; (2) address soil hydrological processes that play a crucial role in maintaining those systems; and (3) highlight useful insights for soil development, plant survival, and soil–plant–water–biota synergy mechanisms. Indeed, the TDHS project has provided a proof of concept for restoration and desert greening initiatives.

Keywords: soil hydrological processes; saline water irrigation; desertification control; shelterbelt

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1. Introduction

Over the last 20 years, a great "green wall" of 436 km has been gradually erected in the center of the Taklimakan Desert, and has helped transform the desert into an oasis [1]. People could not travel very far into the desert in previous decades and centuries because of its hyper-arid environment, known as the "sea of death" in China. It seems that human ingenuity and science can overcome tremendous environmental barriers of fiercely dry and hot conditions to develop new, green ecosystems that provide adaptation services such as protection of infrastructure. The possibility of vegetating large sand-dune deserts as a way to transform their climate to more habitable states—providing global benefits such as carbon sequestration—is increasingly discussed and explored through paleo-evidence and modeling [2]. Here, we report this singular eco-engineering experience (the Taklimakan Desert Highway Shelterbelt (TDHS)), offering proof of how human-aided vegetation establishment on hyper-arid mobile dunes can start and persist at massive scales.

In some contexts, this project may be a successful artifact of humanity's adaption to nature. In China, it has been well known for a thousand years that the Dujiangyan Irrigation System represents a remarkable milestone in human design, adapting to nature. The Chinese government has occasionally examined seawater transport from the eastern coast for use in the Taklimakan Desert. While long-distance water transport might seem impractical, the South-to-North Water Diversion Project to transport water from southern to northern China has caused renewed consideration of such an engineering feat. In Jordan, there is currently an ambitious project to pipe saltwater from the Red Sea to the arid coastal city of Aqaba. The goal is to turn the region into an oasis using seawater that has been desalinated by combining seawater greenhouses and concentrated solar power [3].

In contrast, the Taklimakan "experiment" shows concrete and large-scale evidence that the seed of such transformation is technically feasible by employing local saline groundwater. The portfolio-wide planning of the TDHS may directly feed into the realization of the United Nations' 2030 Agenda for Sustainable Development, due to its potential for carbon sequestration and eco-restoration [4]. These steps would enable the evaluation of outcomes in different social–ecological systems (SESs), e.g., the conditions of ecosystem services, choices of livelihood strategies, and cultural values [5]. Modern culture has developed the techniques to meet the challenges of coordinating or overcoming extreme natural conditions.

The desert is a unique ecosystem. Even though we have modern technology to available re-cultivate our planet, the question remains as to whether this is a wise choice, and why we would celebrate transforming this—one of the last wild places on Earth—into a more artificial territory. The practicality of creating oases as geographic features within desert areas differs from technically feasible. The significance of ecosystem rehabilitation and management requires supportive and regulatory ecosystem services, ecosystem sustainability, and land–atmosphere feedbacks. Most eco-restoration efforts are in temperate regions where the water demands of planted forests can be of concern because the planted trees can exhibit higher evapotranspiration rates than pre-afforestation farmland and grassland [6]. Historically, the unreasonable anthropogenic activity associated with natural shifts has significantly impacted our habitat environment, and has even led to the fall of more than one civilization. For instance, limited understanding of land and water relations left the Tigris and Euphrates valleys saline and barren. Nevertheless, there is no doubt that the existence of vegetation in sandy deserts is influential. Understanding the two-way coupling between vegetation dynamics and the water cycle is critical for the sustainable management of water-limited landscapes [2].

Our study shows the importance of controlling and reclaiming areas overtaken by desert. The most successful context-specific technologies for desert highway and protection systems illustrate how China has tackled those challenges, and provide invaluable guidance for other nations embarking on a similar journey. Given the TDHS having attracted widespread attention concerning saline water utilization and the use of breakthrough technological applications within areas in which standard ecological engineering practices may not apply, this perspective systematically reviews the effects of the TDHS on local saline groundwater utilization, and how it has evolved over time, highlighting valuable insights for fundamental soil hydrological processes associated with soil development and plant survival. We also propose some core principles for successfully implementing such large-scale nature-based solutions with consideration of technology transfer.

2. Overview of TDHS

The TDHS was constructed in 2003, as the initial mechanical checkerboard failed to prevent shifting sands from blocking the highway built in 1997 to access the oil fields [7,8] (Figure 1). However, before the construction of the TDHS, there was no extensive ecological engineering on projects in shifting desert areas. It is essential to select and cultivate appropriate plant species that are drought- and salt-tolerant for wind erosion prevention, and to develop an integrated, innovative irrigation system for afforestation. In 1999, a pilot test was started to assess the feasibility of highway shelterbelt construction. A botanical garden was built within the center of the oasis for trait-based plant species selection and public viewing of the pilot test (Figure 1). By introducing plants that have been pilot-tested in the central oasis, the mobile dunes along the TDHS have been successfully stabilized over the years (Figure 1). At present, a 72–78-meter-wide tree belt has been built along the 436 km of the highway, with a green area of 3128 ha. Despite groundwater with a high saline content, the greenbelt has been most successful, with a 90% plant survival rate [1].

Furthermore, its establishment has improved the biological diversity and soil fauna activity, e.g., 13 herb species have been found since the construction of the TDHS [9].

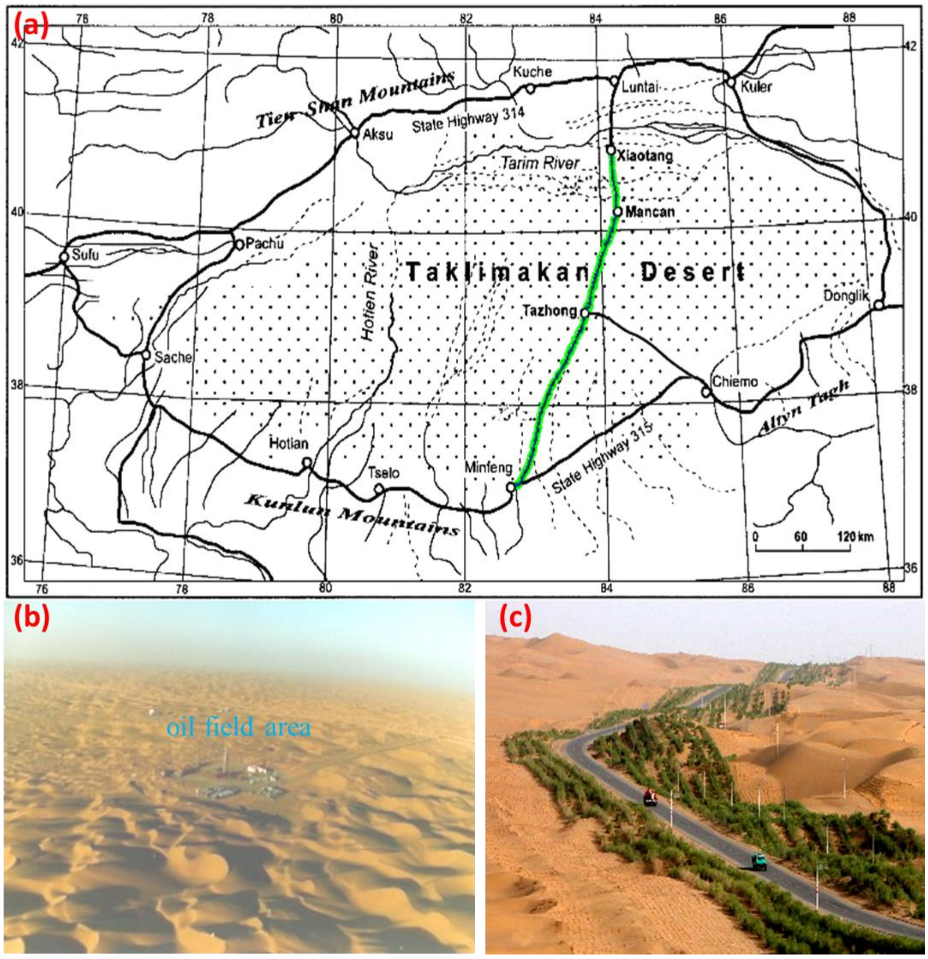

Figure 1. The Taklimakan Desert Highway Shelterbelt across a shifting-sand desert: The highway links Luntai and Minfeng on the northern and southern edges of the Tarim Basin (562 km). The greenbelts on both sides of the highway represent the artificial vegetation establishment (**a**), the oil field area—more than 98% of areas were covered with shifting dunes before the shelterbelt's construction along the Taklimakan Desert Highway (**b**), and the greenbelt today (**c**).

The TDHS's success relied on modern engineering, irrigation, and soil management technologies. First, and most importantly, local saline groundwater irrigation offers advantages and opportunities for plant growth and soil evolution in the mobile sand environment. Large-scale afforestation was possible using specially designed double-branch-pipe drip-irrigation systems to overcome the limitation of regional water scarcity, triggering a rapid evolution of sandy soils that favored further long-term vegetation rehabilitation. We consider saline irrigation to be a feasible way to initialize the sustainability of artificial shelterbelts in similar habitats. What was originally a tree-planting initiative for road construction has evolved into China's response to climate change and a broader development programming tool. Since it was created in a dry desert and nourished with local groundwater, the TDHS project has been highly appraised by many national and international environmental protection organizations—for instance, receiving the highest award of the Chinese Environmentally Friendly Project in 2008. Its success was attributed to modern technologies in engineering design, irrigation utilization, and unique/localized management practices.

3. Soil Hydrological Processes under Irrigation in the Desert

3.1. Saline Water Irrigation for Shelterbelt Engineering in Desert

The near-impossible challenge that this project overcame was the issue of ensuring water sources. The TDHS is irrigated by local groundwater resources, although the water in question is saline. Our observation showed that irrigation with saline groundwater with a salinity concentration of <15.5 g L^{-1} has allowed the plants to thrive with the trend of soil salinity [10]. Due to salt accumulation outside of the root zone, saline groundwater irrigation has not harmed the selected plants' healthy growth. Moreover, the saline water irrigation seems to have provided nutrients to the soil and, thus, stimulated soil development [8]. Consequently, the ecological restoration has increased the silt and clay content, thereby enhancing the water-holding capacity, which is one of the vital prerequisites for long-lasting plant colonization within desert ecosystems [11]. These synergistic mechanisms might be particularly crucial with respect to the initial sandy soil's evolution and the survival of sand-binding vegetation.

Drought, drifting sand blockages, and salt accumulation are three factors that may threaten the sustainability of the artificial desert oasis. In general, precipitated water will all evaporate in the desert air, and the water sufficiency of oasis plants is questionable. Although a water-saving drip-irrigation system was used for our oasis, the soil water content was usually less than 5%, due to the low water-holding capacity of the sandy soil and high evaporative demands. More frequent irrigation schedules (once per 1.5 weeks) have proven better for dealing with drought [12] (Figure 2). Our studies have demonstrated that saline irrigation could significantly influence the dynamics and distribution of soil moisture and salt [13]. Given the buildup of soil salinity through irrigation with saline water, sustainable irrigation strategies are critical to reducing ecological risks [14]. In our case, where an aquifer might not have enough pressure to break through to the surface, a well was bored for pumping water to the surface to irrigate the newly planted trees. This kind of action can ensure the survival of an oasis, and can help jumpstart (i.e., catastrophic shifts) a natural spring that continues to feed an oasis long into the future.

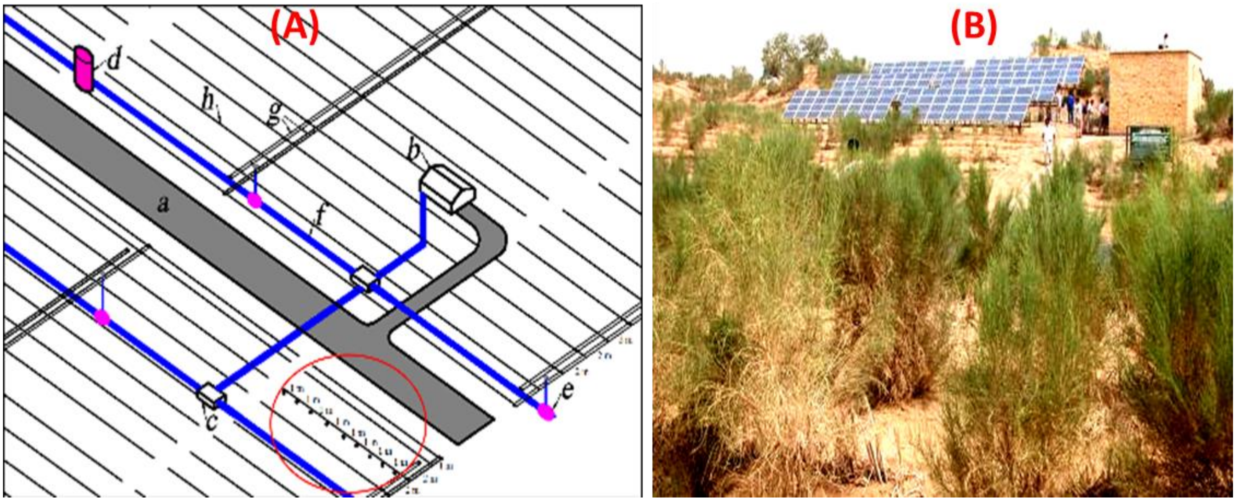

Figure 2. The drip-irrigation system for the Taklimakan Desert Highway Shelterbelt (**A**), which is powered by solar panels in some sections (**B**). (a) Desert highway; (b) well-house; (c) control valve well; (d) connecting well; (e) water valve; (f) main pipe; (g) double-branch pipe; (h) capillary tube. Figure 2 is sourced and updated from [13].

Moreover, a complicated but plausible explanation may be that the decreased Na^+ content was replaced by Ca^{2+} within the root-zone soil, as follows (Figure 3): (i) halophyte root respiration and decomposition of organic matter produced a high partial pressure of O_2 and CO_2 [15]; (ii) the reaction of CO_2 with H_2O (irrigation water and soil moisture) produced H_2CO_3 [16]; (iii) the dissociation of H_2CO_3 and/or N_2-fixing of halophyte roots released H^+; (iv) the reaction of H^+ with $CaCO_3$ resulted in the Ca^{2+}; and (v) the Ca^{2+} facilitated the removal of Na^+. Consequently, the Na^+ may eventually be removed through uptake by halophytes and/or leaching with irrigation water. Although this somewhat complicated process needs additional study, such a process would help explain the decreased soil salinity.

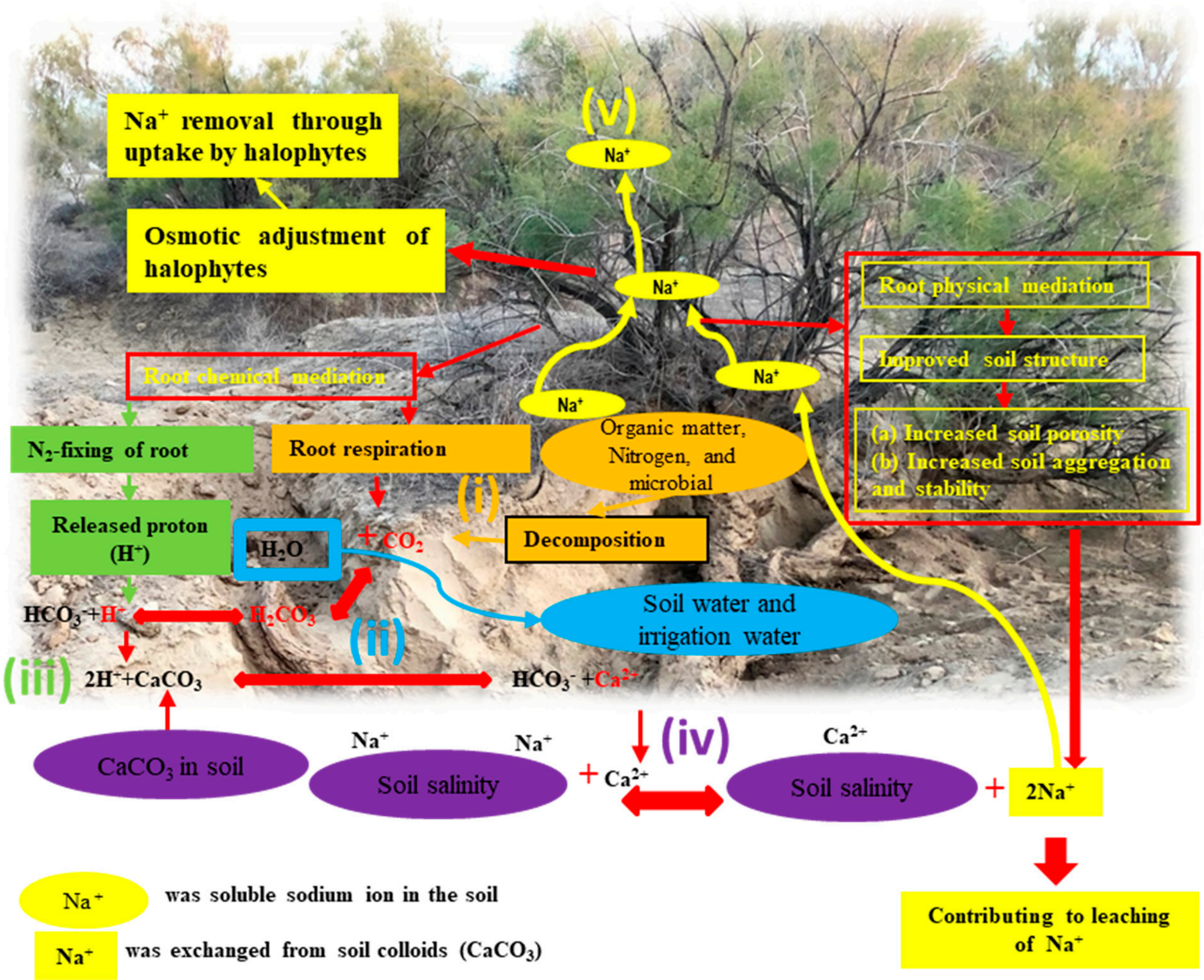

Figure 3. Concept of a suitable mechanism of halophytes' rhizospheres on salt-affected sandy soil under saline water irrigation (an evacuated soil profile of *Tamarix taklamakanensis* is in the background). The figure is referenced and updated from [16].

3.2. Dominant Soil Hydrological Processes under Irrigation Conditions

The local saline groundwater with a salt content of 5–30 g L^{-1} was used to irrigate the TDHS. During drip-irrigation, the salts were transported upward with water for evaporation, and with three dimensions for equilibration of soil water potential differences. The upward movement may lead to salt accumulation at the topsoil. However, this surface salt-accumulation process would weaken, because salty surface crusts may block evaporation [13]. Thus, surface salinization may eventually stop at some point. With a periodically large amount of drip-irrigation, downward water flow would make salts move deeper and prevent their accumulation at a certain depth. Eventually, the salt and water would reach a relatively shallow groundwater level (e.g., 3–5 m) and finish the local water cycle [8]. Recent research also suggests that combining the natural freshwater and desalinated seawater is an excellent strategy to respond to the high water demands for crops [17], along with water pretreatment to reduce salinity as the magnetized, oxygenized, or electrical water approaches.

It should be noted that long-term saline water irrigation frequently results in soil salt accumulation that is detrimental to plant growth. However, our field observations tell a different story. Sandy soil has a low absorption rate, and the saline solutes travel far below the tree roots. The soil EC increased by about 8 mS cm^{-1} within the 0–10 cm soil layer, where no lateral or feeder roots existed, and was less than 1.0 mS cm^{-1} within the 40–60 cm soil layer, where plant roots proliferated. Due to those differences between the salty soil layer and the root zone, our monitoring results showed that saline water irrigation did not harm the plants that had adapted to the local environment.

4. Implications of the TDHS Project

4.1. Underlying Mechanisms to Maintain an Artificial Ecosystem in the Desert

It should be mentioned that the soil ecology has shifted from barren land to vegetated area, which is a significant contributor to sustainability. For >10 years since the TDHS began construction, we have found that the soil structure has progressively improved, as indicated by increased soil aggregate stability and the increased fractal dimensions associated with the increased total N and organic matter contents [18]. The soil is a living miniature ecosystem, exhibiting structured soil processes and functions based on more than sandy particle or soil grain characterization [19]. Yi et al. [20] reported that a rheological state—the so-called omnidirectional integrative constraint "field"—may have formed after adding soil amendment to the sand, providing a prerequisite for soil to become a habitat for plants. However, it has not been determined whether this attribute of binding force exists as a real, measurable variable. Our research found that these amendments improved the shear strength of aeolian soil by enhancing soil cohesion and stabilizing the aeolian soil [21]. Nevertheless, the sand fixation strategy is vital to assist in the governance of loose sand. Additional amendments include reintroducing regulatory species, stimulating soil development with fungi and microorganisms, and re-establishing mutual relationships between species (e.g., vaccination with mycorrhiza) [22].

It could be fascinating for a newly reclaimed ecosystem to apply a structural equation model to understand the relationships between structure, process, and outcome, and to examine the ecosystem services. This is necessary to understand salt-retention mechanisms and soil–plant–water–biota processes further. However, the manifestation of this vast artificial ecosystem remains vague with regard to resource availability and utilization, and to the appropriate management practices for such an enormous heterogeneous area. As a result, the implications of China's integrated land system sustainability remain under-recognized. To identify catastrophic regime shift behavior that results from changes in dryland SESs' structure, functions, and their interactions—and, hence, to determine the tipping point for maintaining ecological sustainability—it is urgently required to unravel the underlying mechanisms and stability from holistic and context-specific perspectives [5].

In this regard, we propose a comprehensive conceptual model of how saline groundwater irrigation can conserve the artificial shelterbelt in the TDHS (Figure 4) [10]. Firstly, saline irrigation satisfies the plants' water needs despite salt accumulation at the soil surface, which minimally affects plants. To some extent, the planted trees can compensate for salt stress through adjustments in root morphology, such as the absence of feeder root growth within the salt accumulation layers. This adaption is one essential process for successful ecological engineering within arid environments. Secondly, the saline water irrigation may input nutrient components into the shelterbelt's soil, further synergizing with vegetative litter decomposition, root growth, and other biogeochemical cycles [23]. Like many other nutrient-constrained environments, litter decomposition within the TDHS is a critical biogeochemical process for C and nutrient cycling that has been primarily affected by the initial contents of C and K, lignin, and cellulose [24]. The accumulation of soil C and nutrients has generally increased throughout the sand-binding vegetation. Thirdly, because of the litter decomposition, microbial activity, and root exudates, the soil nutrient contents of C, N, and P have been significantly improved [25], all of which have contributed to soil development. Consequently, our artificial oasis may have developed into a more self-regulatory construct [16], characterized by the structured clay–organic-rich topsoil, restricted evaporation, and strengthened soil moisture regulation function. While water is the foundation of the oasis' survival, the soil is part of the synergy function for maintaining moisture. It has been shown that soil moisture and texture can affect weather, surface evaporation, and temperature extremes [26]. Furthermore, plant roots may develop tolerance to the local conditions, and can even reach the fringe of the groundwater. As evidenced, naturally distributed *Tamarix* cones, reliant on the relatively stable water sources, reflect adaptations to the different habitats [27]. Therefore, we suggest that shelterbelts and the aeolian sandy soil have developed synergistically over time, with more mature shelterbelts and biodiversity, better soil fertility, and reduced salinity. All of these factors, when considered collectively, have created a benign cycle.

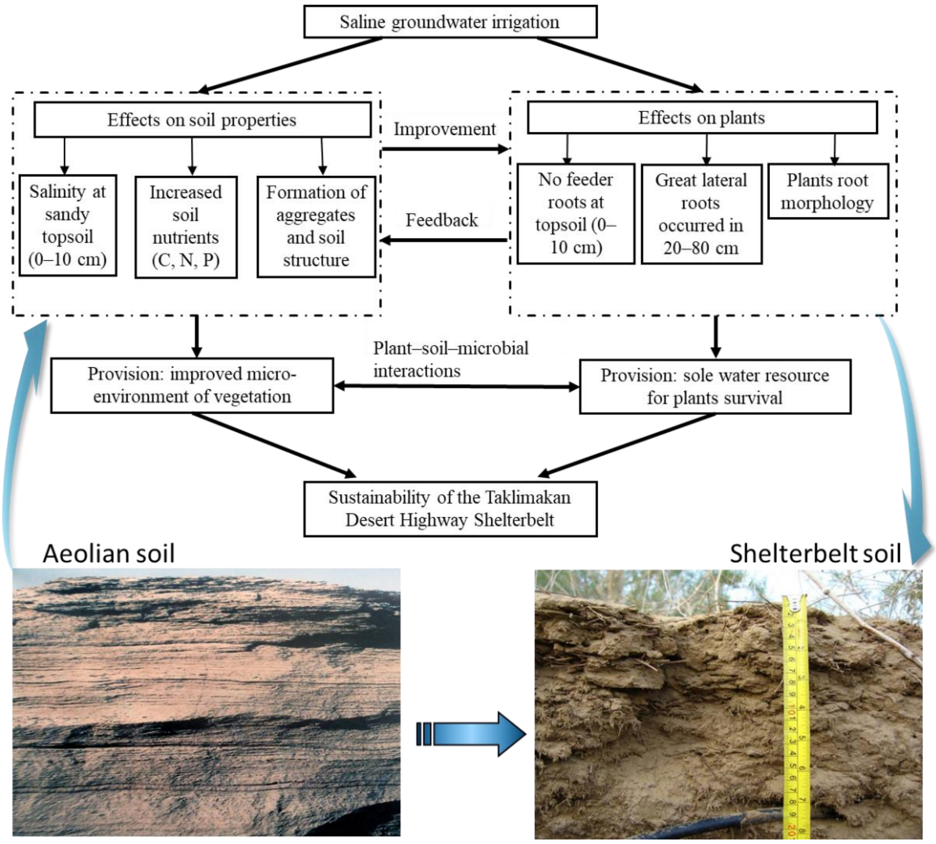

Figure 4. A conceptual model of a plant–soil–microbial system with saline groundwater irrigation. The figure is referenced and updated from [10].

4.2. Implications from China's "Green Wall"

Our studies have shown the importance of controlling and reclaiming areas overtaken by desert. Drylands have the lowest biological productivity, and are home to a significant fraction of global poverty [28]. Over 27% of China now suffers from desertification, making desertification a significant national threat [29]. The Three-North Shelter Forest Program is the most extensive afforestation program globally. It is a 2800-mile network of forest belts covering all of the major deserts and sandy lands within Northwest China. The project is designed to serve as a windbreak to stop sandstorms, halt the expansion of desertification, and restore the land to a productive and sustainable state. The local government has been mobilizing the masses to grow trees from the very beginning and, subsequently, more people have joined the campaign, digging holes for trees and fertilizing the land. As such, there needs to be greater engagement with the land users themselves, who can implement practices that abate land degradation and desertification [30]. Engagement means both education and outreach, highlighting the links between agriculture and ecology, and using innovative strategies to involve stakeholders in gathering and using their local knowledge, thus establishing a new paradigm for water- and climate-smart land management.

Identifying pathways to break the vicious cycle between land degradation and poverty in dryland SESs requires an in-depth understanding of the relationship between the degradation of ecosystem services and the deprivation of humans [5]. Programs must be evidence-based, prioritize cost-effective interventions, and adapt their priorities and approaches over time. Since its establishment, the TDHS has accomplished a series of research and development achievements through long-term monitoring, research, experiments, and demonstrations, and has focused on the key scientific and technological issues urgently needed for management of the fragile regional ecological environment. This study offers a unique laboratory to understand saline and dry environments, showing that they are more sensitive to our interventions than previously thought [29].

5. Sustainable Evaluation of the TDHS

Our project—an ecological engineering feat rivaling the construction of China's Great Wall—may be a successful artifact of human adaption to nature. Beset by water scarcity and growing deserts, China has been actively researching afforestation to create a robust ecosystem-based adaptation for decades. Various pilot projects have tried to mitigate desertification and even desalinate seawater. While long-distance water transport might seem impractical, the Taklimakan "experiment" shows concrete and large-scale evidence that the seed of that transformation is technically feasible by employing local saline groundwater. However, it is expected that the large-scale afforestation may have significantly impacted water resources, e.g., causing increased evapotranspiration and decreased runoff [30]. In concert with China's unprecedented economic growth, ecological restoration within China reduces soil water storage at one of the world's highest rates [31]. Field studies have reported that afforestation has lowered local groundwater levels by between 0.5 and 3.0 m, which may have reduced the survival rates of afforestation to 7–34%, limiting its effectiveness in desertification control [32]. When the results are considered at large scales, the water impacts may be significant, e.g., the large-scale mismatch of plant species' water requirements. For example, afforestation in the Chinese Loess Plateau is approaching sustainable water-resource-use limits and threatening local water and food security [31]. Consequently, China should take bold steps to implement sustainable development for large-scale green engineering.

Can we seek inspiration from ancient water engineering projects that did not use mechanical systems, such as the legendary Hanging Gardens of Babylon or the historic Roman water designs? Indigenous and local knowledge is slowly changing societal water-use perceptions. Close to the TDHS, Xinjiang Karez—an irrigation system of wells connected by an underground channel—is still used today, having been constructed back during the Han Dynasty about two thousand years ago [33]. The synergy of those ancient water delivery systems was planned and constructed without computer-aided design or mechanical systems, but these projects rival and perhaps even exceed the success of many similar designs based on 21st-century innovations [34]. We hope that the intelligent passive systems of the past can be resurrected.

Importantly, no significant long-term impacts of irrigation were found concerning the groundwater level and its salinity [35]. Within the TDHS, the local saline groundwater has been used with our specially designed double-branch-pipe drip-irrigation system, which ensures effective and efficient groundwater use [13] (Figure 2). The borehole wells have been placed at a distance of every 4 km for use on a 2-week irrigation schedule with 20–30 mm of groundwater. Hence, the maintenance cost is mainly used to irrigate and maintain the shelterbelt, at a cost of around USD 0.1 million km^{-1} a^{-1} (Table 1). Although the cost of maintenance is much more than the funding available based on a vehicle tax, this cost has been quickly reduced to >50% of the expense before the TDHS, mainly used to clean the shifting sand and construct the straw checkerboard barriers [36]. The TDHS is of the highest priority for oil/gas exploration and local community development, with a significant eco-environmental value that has not been well evaluated. It is expected to further decrease the cost with the progress of ecosystem services. At present, stable investment mechanisms for combating desertification need to be established, along with financial support policies for guiding the country in its fight against desertification [33]. It is important not to lose sight of these critical issues for regional development in the post-COVID-19 world, as resources and priorities may be shifted away from these crucial development arenas in desert regions.

Table 1. Sand fixation efficiency and cost of the three sand-fixing measures [36].

Control Measures	Effects of Sand Prevention	Input (USD km^{-1} a^{-1})	Ecological Benefits
Mechanical measures	More than 70% of the control measures were ineffective	~0.1 million	No
Biological measures	More than 90% of the artificial shelterbelts were effective	~0.2 million	Improve the eco-environment and increase biodiversity
Chemical measures	Ineffective	~0.15 million	Bring chemical materials to the desert and damage the eco-environment

Nonetheless, dryland sustainability programs need to ensure that the water requirements of species used in the large-scale restoration are compatible with local environmental water availability and quality [5]. If incorrectly managed in desert areas, the increasing aridity, enhanced warming, and rapidly growing population may exacerbate the risk of desertification [37]. Although our practices demonstrate that drip-irrigation is the optimal method for low-cost and highly efficient water usage, our approach needs a long-term assessment, considering that plant salt sensitivity is different for different species. For instance, *Calligonum* is not a halophyte genus, but a xeromorphic genus more susceptible to salt damage. The introduction of an alternative plant may be necessary, and reasonable irrigation methods associated with the growth of halophytes are suggested [38–40]. Only when careful choices are made concerning the irrigation water salinity and the plant species' tolerance for salinity can artificial shelterbelt construction promise sustainable development.

6. Technology Transfer

The TDHS represents a remarkable achievement of land-system sustainability with respect to scientific evidence, governance, and human endeavors [29]. Different regions/countries can learn from the TDHS project and, possibly, adopt similar methodologies to construct sustainable transportation routes or barriers against shifting dunes. With the launching of "the Belt and Road" program, the relevant techniques of our model have been the basis of technical training for transfer to similar habitats that have sustainable development needs for the economy, environment, and ecosystem health. We have currently shared our knowledge on desertification control with some African and Asian countries, e.g., Mauritania, Ethiopia, and Kenya, among others. For example, we proposed an optimization plan named "integrated construction system of 2 zones with 3 protective belts" in Mauritania's capital city Nouakchott. Moreover, international platforms, such as the "China–Africa Cooperation Forum", have established a cooperative mechanism for regularly exchanging experiences, techniques, and investments in desertification control. Some of these forums have been well recognized in a UN resolution as an essential platform for realizing the strategic objectives of the Convention on Combating Desertification.

Current large-scale evidence suggests that, despite enormous investments, China's integrated portfolio of sustainability programs has achieved overall success. Nations need to be prepared to take urgent, decisive, and robust action to ensure environmental sustainability. Before decisions on extensive water resource projects are made, it is necessary to summarize the local ecological, economical, and indigenous knowledge on nature's contributions to people, along with an appropriate decision-making framework of the dryland development paradigm for ecosystem services [41]. Moreover, research on the structure and function of dryland SESs requires sufficient attention. Delgado-Baquerizo et al. [42] found that, regardless of soil age, global climatic and land-use changes will have substantial long-term impacts on the structure and function of terrestrial ecosystems. In terms of both past and present perspectives, as exemplified by the TDHS program's effects across multiple sustainability indicators, our research may provide some keys to success from China's experience, discuss potential risks to large-scale sustainability interventions, and suggest future research priorities.

7. Concluding Remarks

The TDHS project offers the first proof of how human-aided establishment of vegetation on hyper-arid mobile dunes, supported solely by local saline groundwater, can be achieved. Some key points of complex adaptive systems are as follows: (1) Practically, local saline water irrigation within the TDHS shelterbelt has proven helpful for the healthy growth of adaptive plants, and also for the evolution of sandy soil. (2) Our conceptual model provides intrinsic driving mechanisms and structure–function interactions for a catastrophic regime shift of bare sand into vegetated soil. (3) If adequately managed, the TDHS will sustainably represent a successful model utilizing ecological engineering in a harsh environment, given the necessity of plant survival and a self-regulatory adaptation function. As a research agency, we continue to identify research areas needing critical evaluation, assess and verify program effectiveness, and provide scientific and technological support to implementation agencies for quality assurance of sustainability interventions against accepted standards. This program will be revisited and updated regularly to reflect research priorities and new requirements in drylands. We hope that the TDHS will be remembered not only as an engineering accomplishment, but also as a unique system of ecological achievements and a successful example of a large-scale green desert that other arid desert regions can follow.

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