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A comprehensive framework on land-water resources development in Mu Us Sandy Land

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ABSTRACT

Land and water resources are two basic factors for sustaining the development of agriculture. The two are scare resources with rapid social economic development gradually, especially in Mu Us Sandy Land (MUSL) with severe desertification. Arsenic sandstone is a special rock type of MUSL with strong water holding capacity, which appropriately makes up the shortage of sand on water and fertilizer losing. Based on it, a comprehensive framework on land-water resources development was proposed including engineering treatment measures, appropriate irrigation management and farming measures after a series of experiments designed for sandy land treated with arsenic sandstone. Results of the experiments showed that both water content and fertility increased after using a 1:2 arsenic sandstone/sand ratio by mixing both together. An area of 151.3 ha arable land was newly-increased by applying the framework in Dajihan village sandy land of the MUSL, which created direct economic efficiency of 14.1 million Yuan RMB by tomato planting, and obtained 61% of water saving effect compare to untreated sand. The application of the framework in Dajihan village also got huge social-ecological efficiency such as on soil and water conservation, sand-fixing and forming high quality farmland. The framework helped to completed the process from soil synthesize to agricultural production, then to real soil, which transformed the traditional sandy land treatment to sandy land development, and was proved to be practicable and sustainable in local sandy agriculture.

Introduction

Globally, desertified lands occupy approximately 3.6×10^7 km^2 in area, which amounts to about 24.1% of Earth's land surface and desertification affects about one-sixth of the world's population (Wang et al., 2012). Desertification is of grave concern because of its threats to the survival and development of mankind. Until 2009, desertified land in China amounted to about 2.62×10^6 km^2 in area, and it covered 27.3% of the land mass of China. High degree of desertification has severely impaired ecological environment, natural resources, social economy and people's livelihood in China. In past several decades, albeit some effective measures had been implemented as human effort to control desertification, the situation is still severe in Northern China.

General methods mainly focus on sand-fixing, re-vegetation (Hooke and Sandercock, 2012), physical engineering measures such as installing windbreaks and fences (Guo et al., 2002), chemical engineering measures such as spraying chemical cements (Wang et al., 2003) and oil mulch (Amiraslani and Dragovich, 2006). The methods placed too much emphasis on environment effect than on economic benefits. Therefore, those are difficult to be applied widely without support of public and fund.

Subsequently, various methods have been developed to attempt simultaneously achieve economic benefits and desertification controls. An ecological, economic circle framework of sand control and agriculture development, taking household or several households as unit, was proposed in Kerqin Sandy Land (Han and Zhao, 1997). Chen et al. (2003) suggested three treatment modes of vegetation recovery, grassland comprehensive treatment and heavy sandy area control in Hunshandake Sandy Land. In addition, a three circles pattern combined agriculture, forestry and livestock was put forward to accelerate healthy circle of local environment and economy in Mu Us Sandy Land (Liu, 2010). However, those practices showed that desertification was even Hunshandake enhanced when large numbers of vegetation were planted blindly without considering water consumption and evapotraspiration. Supposed that it was beyond the reach of water carrying capacity, it could worsen the situation of land desertification (Zhao et al., 2009). Therefore, increasing the efficiency of water use in agriculture is important to combat land desertification (Portnova and Safriel, 2004), as sand is treated and developed as a kind of resource. Chemical hydrophilic

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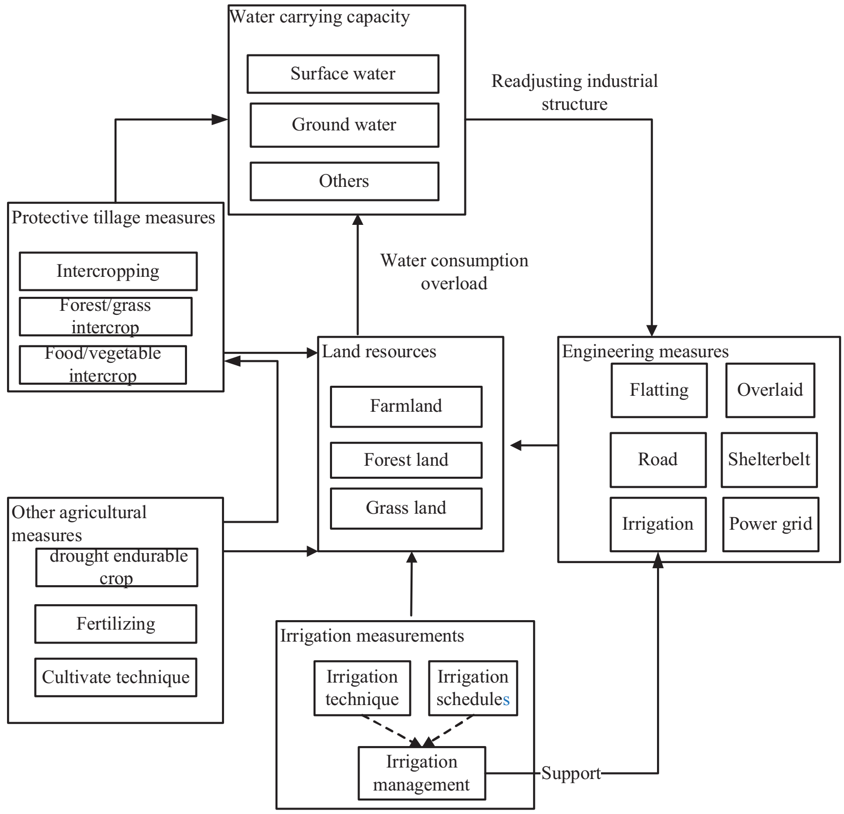

Fig. 1. Comprehensive framework on soil-water resources development.

polymers such as carboxymethylcellulose (RF) and isopropyl acrylamide (BF) (Andry et al., 2009), natural organic matter such as peat, sapropel (Ma et al., 2009), guest soil (Wang and Wu, 2009), clay (Ismail and Ozawa, 2007), and the mixture of clay and organic matters (Djajadi and Abbott, 2012) were added into sandy agricultural soils to improve physical texture and water retention of sandy land respectively; Application of film-bottomed sandy land (Man et al., 2003) was to enhance soil water content and meet water demand of crop growth.

New ideas on the utilization of sand resources

The Mu Us Sandy Land (MUSL) is located at the border of Inner Mongolia, Ningxia and Shaanxi Provinces of China. It covers southeast of the Ordos Plateau along the Great Wall in Northern Shaanxi with an area of about 40,000 km^2. Its mean annual rainfall decreases from above 400 mm in the southeast to 250 mm toward the northwest, and about 70% of which falls between June and August. As MUSL occupies the transitional zone between arid and semi-arid climate, it has more water resources than the west arid sandy land. Because of its latitude, it also receives more solar energy. Solar energy and water resources are essential to sustain the development of agriculture and livestock husbandry. Various efforts have been made to control and develop the MUSL. However, due to the over exploitation of underground water for irrigation, its groundwater table has been declining substantially, which contributed to the spreading of desertification in this region. Therefore, Intensive and water saving utilization are effective measures to solve water crisis so that to achieve sustainable sand control and economic development.

A special rock type of MUSL is a mixture of sandstone, sand shale and argillaceous sandstone, which has loose and easy weathering structure. Calcium montmorillonite, a kind of clay mineral with good water holding capacity, can expand into a form of soft mud when watered, leading to soil erosion and loss of water. Because of the problems created by this clayey material, local residents call it arsenic sandstone, implying it as an environmental “cancer”, along with another hazard desertification. Owing to the strong water holding capacity, arsenic sandstone appropriately makes up the shortage of sand in the water and fertilizer losing. Moreover, it has mineral contents (K, Na, and Ca) higher than those of loess or sand, and the mineral contents are beneficial to crop growth. In view of these facts, we propose the idea to combine the two “hazards”, arsenic sandstone and sand in MUSL to form new land so as to support the local agriculture. Compared with adding hydrophilic polymers, guest soil into sand, the idea of adding arsenic sandstone into sand wouldn’t have residue or pollution and huge cost, and without water loss and soil erosion in the guest soil source area.

The objective of this study is to build an appropriate sand control and utilization framework that can take advantage of the natural conditions of MUSL with the goal of increasing its water utilization efficiency, making it possible to cultivate crops in sand based land with limited water resources. In addition, water saving measure is also considered because this proposed framework will only be effective if its water resources are used in a sustainable manner.

Comprehensive framework on land-water resources development

On the basis of a series of laboratory and field experiments we had conducted at MUSL, a comprehensive framework on land-water resources development was herein proposed, which included engineering treatment measures, irrigation management and farming measures as in Fig. 1 (1) The engineering measures included sand flatting, guest soil overlaid, power grid, road, irrigation and shelterbelt engineering, in which arsenic sandstone

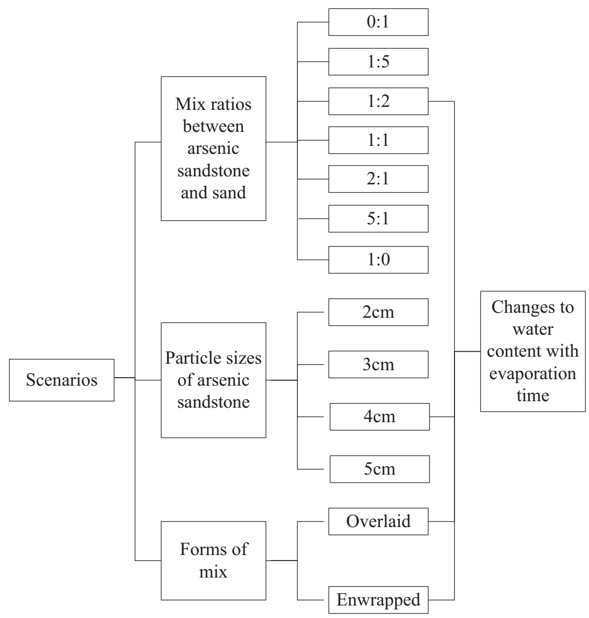

Fig. 2. Experiment design of sandy land treated with arsenic sandstone.

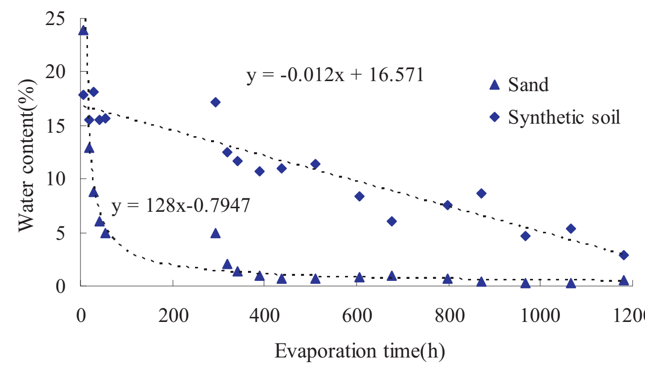

Fig. 3. Water release curve for synthetic soil and sand.

as the "guest soil" was the most important part to ensure the enhance of water holding capacity of sand. (2) The framework for MUSL would be useful only if the expected irrigation water demand could be satisfied. Water saving effect also came from appropriate irrigation technique and irrigation schedules related to the property of the mixture with arsenic sandstone and sand. Effective irrigation management included strategies to promote saving irrigation water by closely monitoring irrigation schedules with respect to soil water content variation, amount and timing of irrigation water to promote optimal crop growth and yield, and to improve the efficiency of water use with minimal wastage, which would always be the goal especially in river basins where water was a scarce resource. (3) The most important agronomic measure was to plant crop species appropriate to the physicochemical properties of the mixture. Potato was the crop selected to plant on the mixture according its growth characteristics and economic benefit or other agronomic factors related to the farm area. However, potato tubers would break existed soil aggregates, it had been suggested that crops would be planted on a rotational basis, between potatoes and other crops such as corn or soybean. Additionally, other relevant farming factors included fertilizers, ploughing, weeding, pesticide application and other measures.

The focus of the framework was changing sand into cultivable sandy land with water holding capacity by adding arsenic sandstone as "guest soil", as well as advanced irrigation techniques and farming measures. When water consumption in sandy land was beyond the reach of local water resource carrying capacity, a readjust to industrial structure would be made to meet sustainable use of water resources.

Mechanism of the framework

Water and fertilizer holding mechanism of the framework

In order to ensure enough moisture to support crops growing on the mixture of arsenic sandstone and sand, combined experiments were designed to analyze the influence on water holding capacity when the mixture had different ratios, particle sizes, and forms between arsenic sandstone and sand, see in Fig. 2. In the experiments, the mixture of arsenic sandstone and sand in ratios of 1:0, 5:1, 2:1, 1:1, 1:2, 1:5, and 0:1 to study water release characteristic. Four particle sizes of arsenic sandstone, 2 cm, 3 cm, 4 cm and 5 cm, with either arsenic sandstone overlaid on the surface of sand or arsenic sandstone mixed with sand, were carried out to determine the water content after a period evaporation when irrigated fully. The combined scenario with smaller water leakage and better water and fertilizer holding capacity will help to make agriculture development on sandy land come true.

As the ratio of arsenic sandstone in the mixture grows, our results showed that the saturated hydraulic conductivity (SHC) was decreases gradually. But SHC decreased slightly after the ratio of 1:2 with only 7% of that on regular sand. Based on the results obtained from experiments conducted on a combination of particle sizes for arsenic sandstone, it seemed that a particle size of 4 cm in diameter was more or less the optimum in terms of water absorbing and water holding capacity. Either smaller particle sizes were easy to be dispersed while larger particle sizes would water to be absorbed slowly, and the outcome was also likely lower soil moisture. It seemed overlaying arsenic sandstone over sand promoted the water absorbing capacity while mixing with sand enhanced its water holding capacity. Therefore, the above two forms could be applied in conjunction with each other, depending on whether water absorbing or water holding capacities are of interest.

Given all that, mixture consists of using a 1:2 arsenic sandstone/sand ratio by mixing both together, was taken as the sample to uncover the water holding capacity of it compared to that of regular sand untreated. Experiments were conducted for 1182 h with initially saturated samples subjected to soil evaporation and infiltration. Fig. 3 showed the time series of the soil moisture data collected at 20–30 cm depth of the mixture compared to that of the regular sand, which showed that mixture managed to control soil evaporation and infiltration loss much more effectively. This advantage of the mixture to retain water by minimizing soil evaporation at the upper zone and infiltration at the deeper zone would be very useful to sustain crop growth and crop yield during dry seasons.

With sufficient moisture in the mixture, nutrients could be dissolved and made more readily available for crops to grow. By the treatment of sand with arsenic sandstone, soil capillarity and porosity were increased which helped to retain water, air and artificial fertilizers such as manure and returning straw applied which were all essential for healthy crop growth. Nutrients such as organic matter would generally continue to improve after several rounds of crops were planted on the mixture for they added fertility to the mixture.

Soil-forming mechanism of the framework

Even though the above proposed mixture had been shown to have enhanced water absorbing property and higher retaining capacities for water and fertilizers, the mixture still required a series of physical, chemical and biological processes before it would

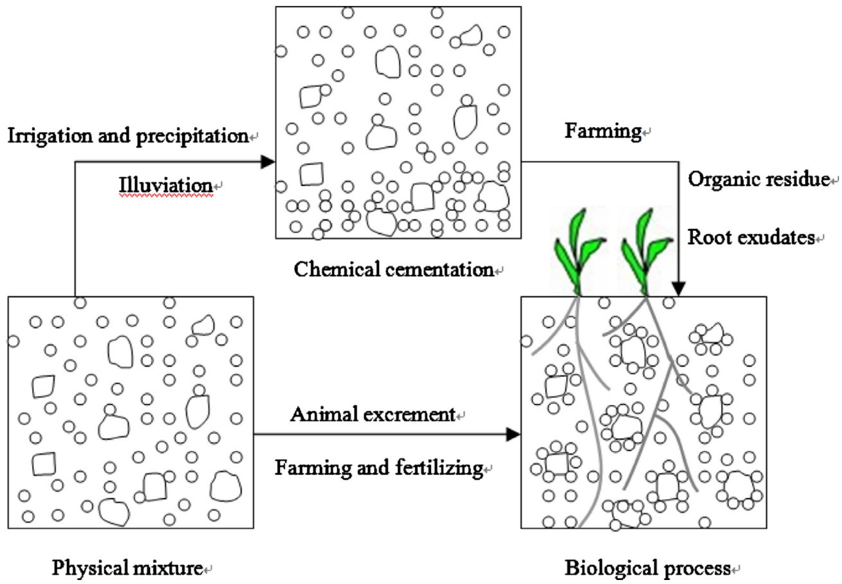

Fig. 4. Soil-forming mechanism of the framework.

function as a “real” soil, as shown in Fig. 4. Physical process provided the initial aggregates and mixture, which was the parent material of the soil. After that, the movable matters, clay, carbonate minerals and silicate minerals, would help in the formation of granular aggregates by chemical cement. However, the aggregates were too hard to extend for root growth. Biological processes, including extrusion by root growth, function of organic matters and microorganisms, were beneficial to aggregate the soil into good texture, building nutrients in the soils, to accelerate the “maturity” of soils. The above processes could remarkably improve soil aggregates that will retain irrigation or rain water at the upper zone instead of it infiltrating to the deeper zone. On the other hand, during droughts, these aggregates in the upper zone would shrink, and then broke the interface between the upper and lower zones, which had the effect of minimizing soil evaporation, and as a result the water use efficiency was increased.

Application effect of the framework

Study site

After reviewing a number of possible study sites in terms of location, climate and water resource condition, the Dajihan village in Yuling, hinterland of the MUSL, was selected as the study site to demonstrate the applicability of the proposed framework. The dominant land type here is barren sandy land. For a long time, Over-exploitation of the land through over-grazing, deforestation, etc., has led to severe degradation and scarcity of land. Water resources for the study site are scarce, and groundwater is the only available water resources coming from fissures between the upper Jurassic and Quaternary sediments. However, prolonged and extensive water waste on agriculture and industry has led to severe decreasing of the groundwater level. In other words, over exploiting the land and water resources far beyond its capacity are literally un-sustainable, which resulted in less land and water resources as well as environmental degradation. To combat those problems, there is an urgent need to promote the conservation of local water and land resources by the framework proposed. And the study site was chosen also because the nearest arsenic sandstone was only 5 km away, so it was logistically feasible to collect arsenic sandstone needed for the study area.

Economic benefit

Sandy land was overlaid by about 10 cm thick of arsenic sandstone which occupied about 15.52×10^4 m^3 in volume in the field. Arsenic sandstone was broken into the designed size, plowed and mixed thoroughly with sand. From this, an area of 161.3 ha sandy land was treated by the engineering, which newly-increased arable land with as area of 153.1 ha. Then, the treated land was planted with potatoes. The potatoes were irrigated by center-pivot sprinklers with water taken from pumping wells and cisterns, and then delivered through pipelines to the land. Then we got a yield of tomatoes 4605 kg per hectare. Although the number was far smaller than the regular production of 30,000 kg per hectare in high quality arable land, the yield obtained from application of the framework created direct economic efficiency of 14.1 million Yuan RMB according the normal tomato price of 2 Yuan RMB per kilogram.

Water-saving efficiency

By applying the framework to the study site, it was possible to achieve a more effective irrigation schedule to meet the water demands of crops in different growth stages, which in the mixture/synthetic soil should be less than in regular sandy soil given the higher water holding capacity and lower water leakage. The averaged water demand for potato crops is approximately 65% of the field capacity of soil as the lowest control line for growth normally. (Wu et al., 2009). Our results showed that the synthetic soil could maintain the soil moisture content above the control line at 20–30 cm below soil surface (the level of the dominant root zone) much longer than the regular sandy soil, e.g., 130 h versus 48 h, respectively. In other words, the water retaining efficiency of the synthetic soil was about 2.7 times higher than that of the sandy soil.

Apparently, using the synthetic soil, an irrigation schedule using a sprinkler system to achieve good crop yield was about 3015 m^3 per hectare for the whole growth period from June 5th to September 10th. Because there was no similar data collected for growing potatoes on regular sandy land in the study site, the irrigation schedule of broomcorn planted in coarse sand of Mauritanian semi-arid regions (Ould Ahmed et al., 2007) were used because of similar water demand process between broomcorn and potato. Water consumption of potato planting was 46.2×10^4 m^3 while it would be 117.1×10^4 m^3 in regular sand, which meant that

70.9×10^4 m^3, about 61% of water consumption in untreated sand, could be saved by the application of the framework. Total average exploitable groundwater calculated is 66.06×10^4 m^3/a in the local area. It showed that water consumption for irrigation could be supported sustainably by groundwater under the application of the new framework.

Social-ecological efficiency

The social-ecological efficiency of the application expressed in three aspects including soil and water conservation, sand-fixing and forming high quality farmland. (1) It improved basic facilities such as road and power grid, and formed cultivated farmland, which led to the enhancement of local agriculture and the improvement of employment opportunities. (2) The application of the framework not only formed new farmland to avoid the scarcity of land resources, but also desertification and soil erosion were decreased obviously at the same time when there were plenty of plant overlaid. (3) By three processes of soil-forming on the sandy land, particles of arsenic sandstone and sand were cemented to form aggregate in the soil, which made the soil had good structure on sand fixing and resisting wind erosion.

Summary and conclusions

Combining engineering measures, efficient irrigation management measures and rational cultivate measures, this study proposed a comprehensive framework on land-water resources development on the basis of a series of experiments. Some conclusions made by the application of the framework on Xiaojihan village, the study site, were showed as follows:

(1) Based on engineering, the framework proposed in this study considered sandy land treatment and agriculture development at the same time and with water resources carrying capacity as its constraints. Remarkable improvements in economic, water saving and social-ecological effects were done in sandy land treated with arsenic sandstone under the framework proposed.
(2) From the application of the framework, organic matters enhanced gradually with several rounds of crops growth, which formed the basis and sustainable accumulation of soil fertility. The application completed the process from soil synthesize to agricultural production, then to real soil, which formed positive feedback to economy and eco-environment.
(3) From passive sandy land treatment to active sandy land development, transformation had been made by using the framework proposed, which was proved to be practicable and sustainable considering the poor water and land resources in local area.

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