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Article

Land Engineering Consolidates Degraded Sandy Land for Agricultural Development in the Largest Sandy Land of China

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Abstract: Sandification has become a major obstacle to China's regional farmland protection, economic development, and ecological civilization construction. It is urgent to adopt advanced ideas and practical actions to reverse the sandy land. Structural consolidation theory was introduced to rehabilitate sandy land into farmland by soil body building, soil layer reconstruction, and soil quality improvement. A field experiment was conducted in Mu Us Sandy Land to explore the effects of blended guest materials (red clay and loess) with sand at four volume ratios (1:1, 1:2, 1:3 and 1:5) on crop yields, soil properties, and root growth. Red clay and loess significantly increased clay and silt contents and regulated the soil total nitrogen concentration and organic matter content during the critical growth stage of maize. Red clay and loess had a significant promotion of maize and soybean yields at a volume ratio of 1:3. The maximum potato yield was 42,501 and 37,332 kg ha^{-1} in red clay treatment at a volume ratio of 1:5 and in loess treatment at a volume ratio of 1:3, respectively. Lowest root biomass in surface soil and surface/subsoil root biomass ratio mediated maize growth in red clay treatment. Red clay was considered as the better material to rehabilitate sandy land and develop agriculture in the long-term according to the engineering costs and crop yields. Water sustainable utilization strategies and potential popularization areas of sandy land structural consolidation should be enhanced in the future.

Keywords: sandification; land engineering; Mu Us Sandy Land; soil particle; structural consolidation

1. Introduction

Land and soil are essential natural resources related to the prosperity of humanity and the maintenance of all terrestrial ecosystems [1]. Rapid urban expansion and unsustainable land management have increased the eco-environmental pressure and declined the health of global land resources [2,3]. Lal et al. [4] reported that a quarter of the Earth's land is degraded. Worsening land degradation is undermining the well-being of 3.2 billion people [5]. United Nations 2030 Agenda for Sustainable Development Goals aims to strive towards land degradation neutrality [2]. Technology innovation for restoring degraded land quality and productivity is important to mitigate the threats of food security and avoid civil strife and political instability [6]. However, 79% of community-based sustainable land management technologies are focused on land degradation prevention and reduction, whereas only 20% mention the goal of restoring degraded land [7]. Therefore, more land rehabilitation and restoration technologies should be designed and implemented to reverse and utilize the degraded land.

China is one of the most affected countries in the world in terms of the extent, intensity, and economic impact of land degradation [8]. Sandy land accounts for over one-sixth of China's territory. Sandification means a rapid increase in the area of newly sandified land, resulting in land degradation and land productivity decline [9]. Sandification has become a major challenge to regional farmland protection, economic development, and ecological civilization construction. China offers some prescriptions in combating sandification to the other countries and regions, including governmental leadership, public participation, science and technology support, and legal guidance and policy incentives [10]. The total sandy land is shrinking by 1980 km^2 annually, compared with an annual expansion of 10,840 km^2 at the end of the last century. However, in some regions, sandification has continued to expand due to overconcern of vegetation cover, and disconnection between science and policy [11]. Afforestation in arid areas lacks sufficient precipitation or irrigation to sustain tree survival in the long term [12]. In addition, forbidden grazing and excluded livestock, as well as the Grain-for-Green Program, have resulted in regional poverty because residents cannot find ways to make a living. The formidable challenge is achieving synergy between socioeconomic development and environmental protection [13]. Therefore, the strategy is to adopt advanced ideas and practical actions that can accomplish both sandy land control and sustainable utilization.

China has extremely scarce farmland resources owing to its huge population. Farmland is insufficient, and the human–land relationship is not harmonious in sandification areas. China's land-system sustainability programs have achieved considerable overall success since 1998 [14]. Sandy land is an important resource that can be cultivated into new farmland. In recent decades, various materials and methods have been adopted to improve the sandy land structure. Fly ash is used as a soil ameliorant for increasing water holding capacity of sandy soils [15]. Microalgae help to transfer nutrient materials from wastewater to desert [16]. A stable and easily peeled microalgal biofilm crust structure is formed on the sand surface due to the binding and cementing between sand particles and microalgal filaments and secreted exopolysaccharides [17]. However, natural organic matter, such as sediment, peat, sapropel, and municipal sludge, has limited sources or inconvenient transporting [18]. Man-made biochar has small and transient effects on the physical and chemical properties of sandy soil [19]. Chemical hydrophilic polymer and viscous paste are criticized for being expensive, unsustainable, toxic, and dangerous [20,21]. The challenges are not only to search for cheap, convenient, and environment-harmonious materials but also to develop innovative conservation tillage technologies and utilization modes.

China has strengthened its efforts to prevent and utilize sandification, with the construction of various production bases for grain, fruits, and nuts. According to the 13th Five-Year-Plan period (2016–2020), a total amount of 100 thousand km^2 of sandy land needs to be improved. It focuses on sustainable sandy land utilization and agricultural development. Feng et al. [13] suggested that sustainable engineering measures, modern production technologies, and carefully organized production processes are essential to consolidate and utilize sandy land. In sandy land areas, the integration between sandy land consolidation, agricultural production, and precision management needs to be established for sowing improved crop varieties on high-quality land. Therefore, the paper aims to (1) present the sandy land consolidation theory and engineering practice; (2) consolidate sandy land into farmland for agricultural development based on the field experiment; (3) propose the engineering technologies and agricultural development modes for national sandy land consolidation and utilization.

2. Sandy Land Diagnosis and Structural Consolidation

A new idea was introduced to transform sandy land into farmland through phases of diagnosis, prescription, and process. Sandy land has defects of scare clay or silt particles, loose soil structure, and limited water and nutrients retention capacity based on the element, structure, and function diagnosis. Corresponding restoration prescriptions are aggregate arrangement, structure reorientation, and nutrient reassembly. In the consolidation phase, guested clay or silt materials are used to construct the ideal soils after soil body building, soil layer reconstruction, and soil quality improvement (Figure 1). Newly constructed farmland is a mixture of sand, clay, and silt, favoring water retention, air circulation, and fertility.

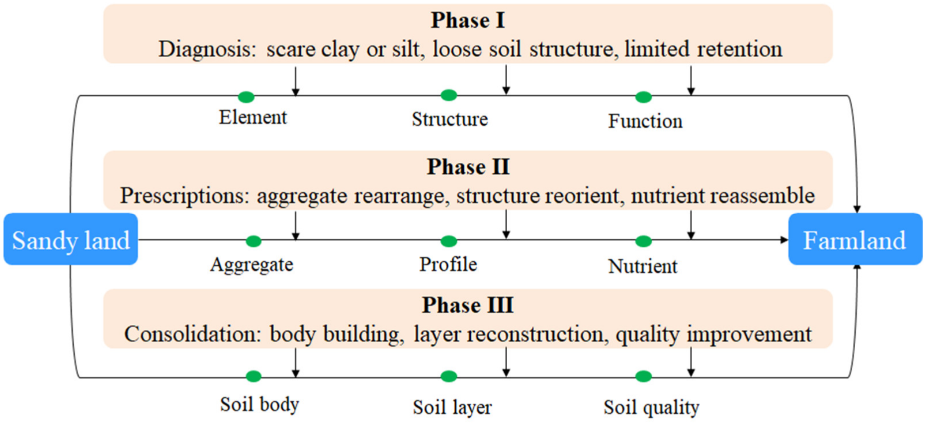

Figure 1. Theoretical framework of sandy land diagnosis and structural consolidation.

A poor sandy land structure can be converted into stable soil structure by implementing engineering and agronomic measures (Figure 2). In northern China, tertiary red clay deposits are widespread and distributed surrounding sandy land [22]. Abundant clay particles in red clay are unsuitable for crop root growth while perfectly suitable for sandy land structural consolidation. In the engineering period, original sandy land is mechanically leveled and compacted. Vegetation branches and roots are removed during land leveling. Guest red clay or loess materials are firstly broken into particles with grain sizes less than 4 cm [23]. Flat sandy land is overlaid with broken red clay or loess particles at a suitable thickness. Then, extra sand with a certain thickness is spread on top of the guest materials. Parts of the guest materials are thoroughly blended with sandy land using deep tillage machines with depths of 30 cm to construct the cultivated horizon. Deeper remaining guest materials are used to construct the density horizon. Local crops are planted in the newly mixed soils after land leveling. Reconstructed soil structure includes the loose cultivated horizon, tight density horizon, and C-horizon, which consists of sand and clay or silt compounds, single clay or loess, and original sand, respectively (Figure 2).

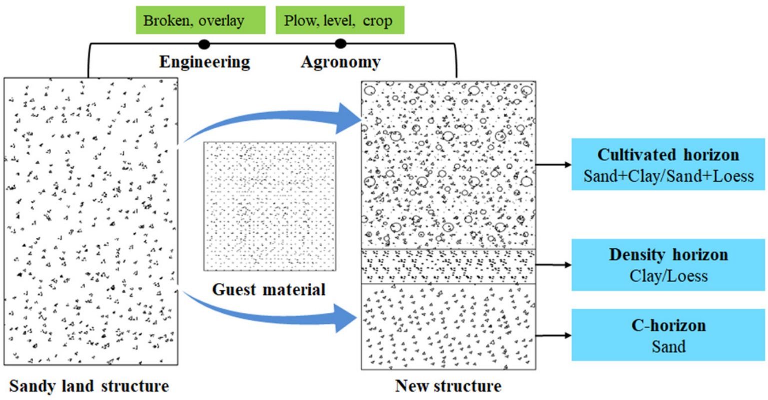

Figure 2. Comprehensive framework of sandy land structural consolidation practices.

3. Field Experiment in Mu Us Sandy Land

3.1. Materials and Methods

3.1.1. Site Description

Mu Us Sandy Land is one of China's four major sandy lands, with an area of approximately 42,200 km^2. It is adjacent to the Loess Plateau in China to the southeast. Mu Us Sandy Land involves ten counties of Shaanxi province, Ningxia Hui, and Inner Mongolia Autonomous Regions. The typical continental semiarid climate dominates the region, with a mean annual temperature of 6.0~8.5 °C and mean annual precipitation of 250~400 mm [24]. The dominant soil type is Aeolian sand. Wetting trends and ecological restoration projects have contributed to an important foundation for vegetation improvement [25]. The south edge of Mu Us Sandy Land was regarded as the second granary construction base of Shaanxi Province in 2013 due to the relatively abundant water resources, improved crop varieties, and plentiful heat energy [23]. Local government has established sandy land consolidation projects to develop agricultural production. Farmers have rehabilitated the existed sandy land to improve land productivity using simple restoration measures, such as leveling, straw returning, and fertilization. However, traditional systems of sandy land consolidation measures are either limited soil fertility or lower crop productivity.

A field experiment was conducted at Yuyang district (38°22′43′′ N, 109°26′05′′ E) of Yulin City, Shaanxi Province. The original landscape was barren sandy land, with a soil texture of 94.10% sand, 3.20% silt, and 2.70% clay. In the surface soil (0–20 cm), the total nitrogen (TN) content is 0.08 g kg^{-1}, available phosphorus content is 7.42 mg kg^{-1}, available potassium content is 39.34 mg kg^{-1}, and the soil organic matter content is 0.9%. The total amount of precipitation is 621.7 and 651.5 mm for 2016 and 2017, respectively. Precipitation occurring in the crop season from May to September accounted for about 77.00% and 79.54% of 2016 and 2017, respectively. Red clay and loess are widely distributed along the Great Wall in the Yulin area [26]. The red clay and loess used in the field experiment were collected from Qinhe town of Yulin City, with a total material and transport price of 5 and 3 USD m^{-3}, respectively.

3.1.2. Engineering Design and Crop Management

Sandy land structural consolidation engineering was carried out in April 2015. Red clay and loess were used as the guest materials to construct cultivated horizon and density horizon with a thickness of 30 and 15 cm, respectively, according to the introduced engineering practice in Figure 2. Eight treatments included dry mixtures of red clay and sand at volume ratios of 1:1 (R1), 1:2 (R2), 1:3 (R3), 1:5 (R4), and dry mixtures of loess and sand at volume ratios of 1:1 (L1), 1:2 (L2), 1:3 (L3), and 1:5 (L4) were arranged. Each treatment (5 × 30 m) had three replicates. It is noted that we did not set up sandy land as control. First, the native sandy land has not been directly used for planting crops due to infertility. In addition, our objectives are to develop the sandy land consolidation engineering technologies and select the agricultural development mode. Local maize (Shandan 609), soybean (Tiedou 61), and potato (Shepody) have been planted in the new consolidated land since 2015. Fertilizer was applied according to the traditional recommendations (Table 1).

Table 1. Crop varieties and fertilization management measures.

Crop	Variety	Fertilization (kg ha^{-1})		
		N	P_2O_5	K_2O
Maize	Shandan 609	315	75	90
Soybean	Tiedou 61	100	25	50
Potato	Shepody	175	60	225

3.1.3. Sampling and Measurement

In 2016 and 2017, crop yield was estimated by manually harvesting each treatment. Maize and soybean were oven-dried to a constant weight at 80 °C. Soil samples and root biomass were only measured for maize treatments in 2017. Soil samples were collected four times from the surface layer (0–20 cm) at the seeding stage (3 May), elongation stage (10 June), booting stage (16 August), and harvest stage (12 October). TN and soil organic carbon concentrations in the bulk soil were determined by dry combustion using the Kjeldahl method and dichromate oxidation method, respectively. SOM was calculated using the efficiency factor of 1.724 [27]. The soil particle composition was only measured at the harvest stage using a laser particle analyzer (Mastersizer 2000, Malvern Company, Malvern, UK), according to [28]. Root–soil mixture (length × width × depth = 20 × 20 × 40 cm) in red clay treatments was excavated using a plant-centric excavation method. Root–soil mixture was divided equally into two parts with the same depths of 20 cm in order to examine the differences of root biomass in the surface soil and subsoil. Root biomass was over-dried to a constant weight at 80 °C after washing and selecting.

3.1.4. Statistical Analysis

One-way ANOVA with the least significant difference (LSD) test was applied to examine the differences in crop yield, soil particle composition, soil TN concentration, SOM content, and root biomass in different treatments. All statistical analyses were conducted using the SPSS software (version 16.0), and differences were considered significant at $p < 0.05$ unless otherwise stated. All figures were drawn using Sigmaplot software (version 10.0).

3.2. Results

3.2.1. Engineering Cost

A total of 30, 25, 23, and 20 cm red clay or loess were guested to construct the cultivated horizon and density horizon in four volume ratios. Guest materials with a thickness of 15, 10, 8, and 5 cm were blended with sand to construct the cultivated horizon with a thickness of 30 cm in different treatments. The density horizon was constructed using equal 15-cm guest materials for each treatment. Engineering costs ranged from 11,200 to 16,200 USD ha^{-1} for red clay treatments, while lower engineering costs ranging from 10,200 to 7200 USD ha^{-1} were found for loess treatments. Material cost contributed 83.33~92.59% of the total engineering cost. Each treatment had the same tillage cost of 1200 USD ha^{-1} (Table 2).

Table 2. Engineering costs of sandy land structural consolidation in different treatments.

Treatments	Guest Materials Thickness (cm)		Cost (US Dollars ha^{-1})		
	Cultivated Horizon	Density Horizon	Material	Tillage	Total
R1	15	15	15,000	1200	16,200
R2	10	15	12,500	1200	13,700
R3	8	15	11,500	1200	12,700
R4	5	15	10,000	1200	11,200
L1	15	15	9000	1200	10,200
L2	10	15	7500	1200	8700
L3	8	15	6900	1200	8100
L4	5	15	6000	1200	7200

3.2.2. Crop Yield

In 2016, neither red clay nor loess had any significant promotion effects on maize and soybean yields, while the lowest potato yield was found in R1 and L2 treatments (Figure 3a,b). In 2017, R3 treatment had the maximum maize and soybean yields of 9299 and 4550 kg ha^{-1}, respectively. The highest potato yield was found in the R4 treatment, while the lowest maize, soybean, and potato yields all emerged in the R1 treatment (Figure 3c). For loess treatments, the L3 treatment had the highest maize, soybean, and potato yields of 8598, 4389, and 37,332 kg ha^{-1}, respectively. The lowest maize and potato yields were found in the R4 treatment, and the lowest soybean yield was found in the R1 treatment (Figure 3d).

3.2.3. Soil Properties

The effects of red clay on silt and sand contents were not significant between the R3 and R4 treatments (Figure 4a). Significant differences of soil TN concentration were found at seeding and harvest stages (Figure 4c), while significant differences of SOM content were found at booting and harvest stages (Figure 4e). The R1 treatment had the highest soil TN concentration of 0.17 and

0.14 g kg^{-1} for seeding and harvest stages, respectively (Figure 4c). The R3 treatment had the highest SOM content of 0.16% and 0.20% for booting and harvest stages, respectively (Figure 4f).

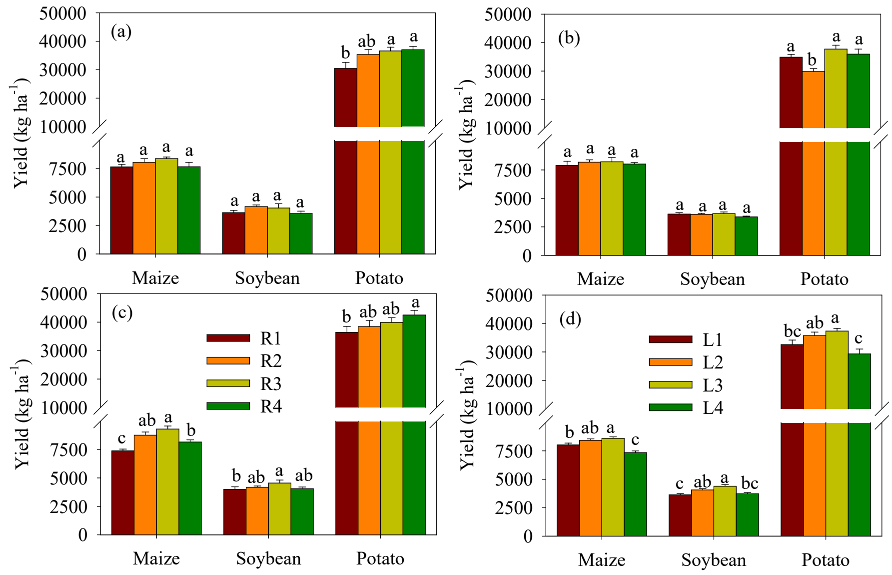

Figure 3. Crop yields in different treatments over the two growing seasons of 2016 (**a**,**b**) and 2017 (**c**,**d**). Different lowercase letters indicate significant differences among the different treatments.

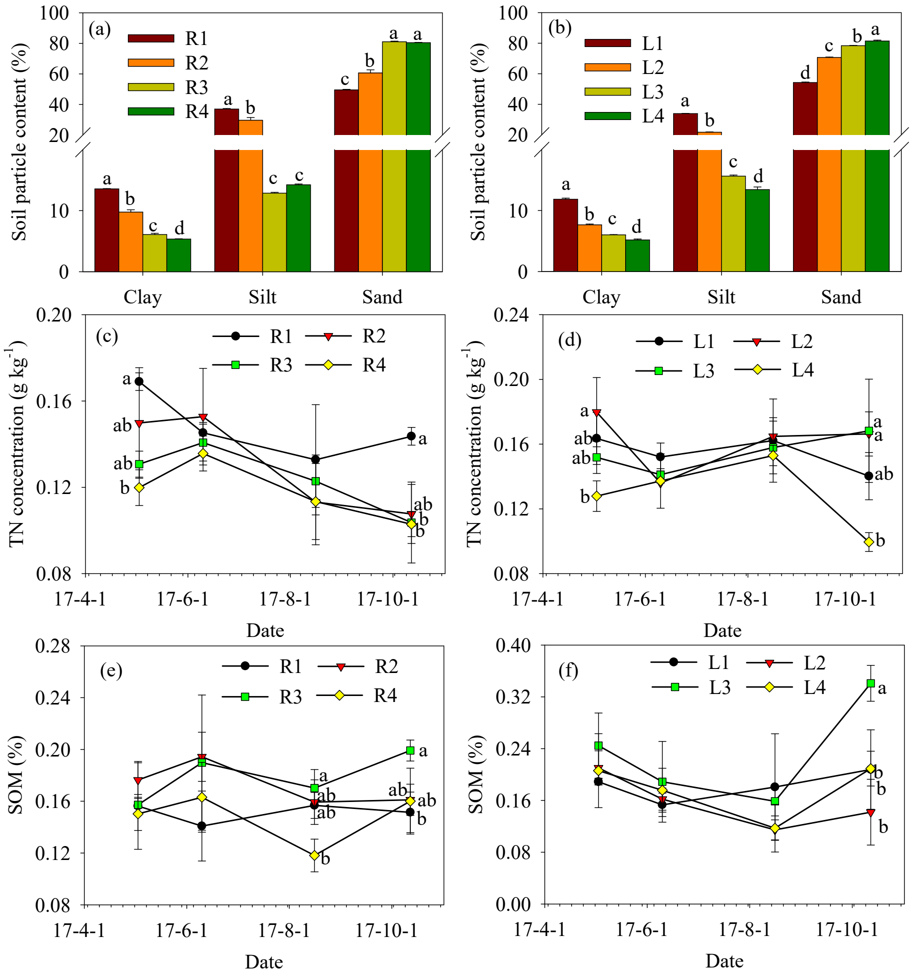

Figure 4. Soil particle content (**a**,**b**), TN concentration (**c**,**d**), and SOM content (**e**,**f**) in different treatments. Different lowercase letters indicate significant differences among the different treatments.

Loess addition significantly increased clay and silt contents, while it significantly decreased sand content (Figure 4b). Significant differences in soil TN concentration were found at seeding and harvest stages (Figure 4d), while a significant difference of SOM content was only found at the harvest stage (Figure 4f). The L2 treatment had the highest soil TN concentration at the seeding stage, with a value of 0.18 g kg^{-1}. The L3 treatment had the highest TN concentration and SOM content at harvest stages (Figure 4d–f).

3.2.4. Root Biomass

In surface soil, the R1 treatment had a higher maize root biomass, with a value of 12.37 g $plant^{-1}$, than the R3 treatment with a value of 8.23 g $plant^{-1}$. There were no significant differences among the four treatments in the subsoil. The surface/subsoil ratio was 5.26 in the R1 treatment, which is 2.21 times that in the R3 treatment (Table 3).

Table 3. Effects of red clay on maize root biomass in surface soil and subsoil. Different lowercase letters indicate significant differences among the different treatments.

Treatments	Root Biomass (g $plant^{-1}$)		Surface/Subsoil
	Surface Soil	Subsoil	
R1	12.37 ± 0.90^{a}	2.68 ± 0.68^{a}	5.26 ± 1.27^{a}
R2	9.12 ± 1.37^{ab}	3.41 ± 0.17^{a}	2.68 ± 0.40^{ab}
R3	8.23 ± 0.63^{a}	3.87 ± 0.97^{a}	2.38 ± 0.58^{b}
R4	11.04 ± 1.12^{ab}	3.42 ± 0.64^{a}	3.60 ± 1.07^{ab}

4. Discussion

China has found workable solutions to deal with sandification. Sandy land controlling technologies include engineering, biological, and chemical measures. However, physical and mechanical engineering measures are costly and have difficulty in implementation. A poor sustainable sand stabilization effect of biological and chemical measures has limited a large-scale application [20]. According to the 13th Five-Year Plan for the National Economic and Social Development of China, more than 50% of governable sandy land should be effectively controlled by 2020. Comprehensive sandification prevention, control, and utilization strategies have been emphasized in governmental policies. Looking for mature sandy land restoration techniques and well-tested practices have become an essential demand in achieving synergy in ecological protection and farmland supplementation. Land engineering aims to increase land use range and promote land productivity by way of soil organic reconstruction [29]. Integrated land engineering technologies with agronomy measures can transform degraded sandy land into usable farmland (Figure 2). Red clay and loess are used as the clay and silt particles to restore the sandy land structural defects. Reconstructed land is cultivated, and density horizons make the sandy land into farmland, with ideal soil aggregate, layer, and profile (Figures 1 and 2).

The economic budget between land engineering costs and benefits of crop yield is an important factor to be considered for agricultural development after implementing sandy land consolidation engineering. A potato planting mode can compensate for the engineering costs within one year, while a maize planting mode will spend 10 years and 7 years in order to break even the engineering costs for R3 and L3 treatments, respectively. Although red clay had higher engineering input than loess (Table 2), crop yields in red clay treatments were all higher than those in loess treatments (Figure 3). Take potato, for example, where the R4 treatment can obtain an extra 1550 USD ha^{-1} than the L3 treatment, according to the local potato price of 0.3 USD kg^{-1}. The corresponding higher engineering input of 3100 US dollars ha^{-1} will be compensated within two years. Therefore, we consider red clay as the better material to consolidate sandy land and develop agriculture in Mu Us Sandy Land. Furthermore, sandy land consolidation engineering has a higher crop yield than the local average yield. Households can get higher productivity and land transfer rent from new consolidated sandy land. Sandy land consolidation engineering provides more productive farmland for agricultural industry development. Local households are employed in land engineering and crop management jobs. Sandy land consolidation engineering can promote rural poverty alleviation from the aspects of higher land productivity, increased land transfer rent, and extra wage income [30].

Crop yields did not increase along with the increased guest material input. Optimized agricultural development modes were selected by coupling soil ecological suitability and crop physiological adaptability in our study. In 2017, maize and soybean had higher yields in R3 and L3 treatments (Figure 3). The highest potato yield occurred in R4 and L3 treatments, respectively (Figure 3). These were attributed to the moderate nutrient retention and releasing rate in the newly consolidated land. Soil structural and hydrological properties, as well as nutrient availability, depend on soil texture related to soil particle distribution [31]. Guest red and loess materials significantly increased soil clay and silt contents (Figure 4a,b). However, too loose or too tight a soil structure is a disadvantage for nutrient preservation and release. Relative tight soil structure in the R1 treatment gave rise to the highest soil TN concentration at harvest time (Figure 4c) due to the lower nutrient release rate. Less tight soil structure in the L4 treatment resulted in the rapid recycling of soil nutrients and lower soil TN concentration and SOM content at harvest time (Figure 4d,f). In addition, crop yield increased by promoting root biomass and distribution. Nutrients bioavailability in the soil profile affects root growth and proliferation [32,33]. In red treatments, maize root growth was modulated by nutrient stresses. The highest surface/subsoil ratio can mediate the adaptation of maize in the R1 treatment by increasing the root biomass in surface soil (Table 3) and the ability to take up water and nutrients [34]. Nutrient release rate and maize root morphological parameters need to be further studied for revealing the underline mechanisms.

Water utilization should be noted when promoting sandy land consolidation technologies. Previous large-scale sandy land development and unreasonable utilization strategies led to the decline of the groundwater table and quality [35]. Sandy land consolidation and agricultural development should be well managed to avoid the depletion of water resources, which result in a worsening of sandification. Guest red clay and loess have many clay and silt particles that can enhance the water-holding capacity of sandy land. In the studied area, better water-holding capacity and higher water-use efficiency were found after blending arsenic sandstone with sand in a laboratory experiment. A field experiment showed that about 61% of irrigation water in the potato growth period was saved compared with water use in sandy land without treatment [36]. Our preliminary results showed that water-saving was about 70.02%, 51.02%, and 30.87% for potato, maize, and soybean planting, respectively, by guesting red clay and using drip fertigation technologies [30]. That means the same water can irrigate more crop-planting areas under the application of the model. Furthermore, precipitation can provide about 500 mm yr^{-1} for crop growth in our studied area. A gradually wetting climate will benefit sandy land consolidation and agricultural development in Mu Us Sandy Land [25]. However, regional water resource carrying capacity and water use scenarios in the middle or western areas of Mu Us Sandy Land should be evaluated before sandy land consolidation. A combination of land engineering and modern water-saving technologies can achieve efficient utilization of water and soil resources in sandification areas. In addition to red clay spatial distribution, profile depth is valuable to calculate resource storage and practical potential. Wang and Liu [30] estimated that red clay resources can consolidate 19.72% of China's total sandy land to plant corn or soybean or consolidate 22.18% of China's total sandy land to plant potato. Badain Jaran Desert and the south edge of Mu Us and Khorchin Sandy Land were suggested as the potential popularization areas. Currently, practical, potential, and demonstration areas should be confirmed immediately in Mu Us Sandy Land, especially in the studied Yulin City.

5. Conclusions

Red clay treatments have higher engineering costs and crop yields than those for loess treatments. Red clay was recommended as the better material for sandy land consolidation and agricultural development in Mu Us Sandy Land. Promoting of red clay on maize yield resulted in moderated nutrient retention and release rates and improved root distribution. In the future, water sustainable utilization strategies and potential popularization areas should be noted. A long-term study should be enhanced to reveal the mechanism of guest materials on crop yield and soil structure formation.

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