The effect of gravel-sand mulch on soil moisture in the semi-arid loess region

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Abstract In the semi-arid loess region of northwest China, the use of gravel and sand as mulch has been an indigenous farming technique for crop production for over 300 years. This study was carried out to quantify the effect of gravel-sand mulch on soil water in the semi-arid loess region of northwest China using HYDRUS-1D code. The field experiment (4 April 2001–12 July 2001) consisted of two treatments: no mulching as a control and gravel-sand mulching. The results show that the gravel-sand mulch field can provide a more favorable soil moisture environment for plant growth. In the initial stage of watermelon growth, there was higher soil water content in the gravel-sand mulch field, which was very beneficial to the germination of watermelon. Gravel-sand mulch can improve soil moisture conditions. It is effective in reducing evaporation and improving transpiration. Gravel-sand mulch can improve the infiltration of rainwater to depth. After a little rainfall, the soil moisture gathered at 12–30 cm depth soil layer for the gravel-sand mulch field and at 0–20 cm depth soil layer for the no-mulch field. The results indicated that the higher soil moisture content in the layer (12–30 cm) may enhance watermelon growth.

Key words gravel-sand mulching; HYDRUS-1D; northwest China; semi-arid; soil moisture movement

INTRODUCTION

Precipitation is the major water source for agricultural production in the semi-arid region of northwest China. In the northwestern Loess Plateau, the mean annual precipitation is 250–350 mm with a coefficient of variation of 35%. Over 70% of the precipitation falls during the monsoon months between June and September. Only 19–24% of rainfall occurs between May and June when the crop water requirement accounts for 60% of the total required by the crop (Li *et al.*, 2001). Consequently it is necessary to maximize rainwater utilization for successful agricultural production. The use of gravel and sand as mulch (known as Shatian or sandy field in Chinese), to conserve the sporadic and limited rainfall for reliable crop production, may date back to the period of the Qing Dynasty, about 300 years ago, in the semi-arid loess regions of northwest China (Wang & Sun, 1986; Li, 2000). Gravel and sand mulching is a traditional technique that is still practiced in the loess area of China. However, there have been few systematic studies of the effect of gravel-sand mulch on soil water in the semi-arid loess region of northwest China.

Gale *et al.* (1993) introduced the creation and maintenance of gravel-sand mulched fields (GSMF) and briefly discussed some of the principles underlying this successful agricultural practice, but the documentation remained descriptive and lacked experimental data. Li (2003) investigated the effects of gravel-sand mulch on soil hydrological processes, thermal properties and erosion in short-term tests (for example, one day) under specific weather conditions (such as rain, wind, etc.). Trials in fields with and without surface gravel-sand mulch were conducted in 2001 and 2002 to examine the effects and economic feasibility of supplemental drip irrigation on watermelon (*Citrullus lanatus*) production in the Loess Plateau of northwest China (Wang *et al.*, 2004).

Numerical simulation is an efficient approach to investigate the effect of gravel-sand mulch on soil water moisture in the semi-arid loess region and it can provide a general idea of the principles and methods of management of the GSMF. However, as far as we know, numerical simulation has not been used to study the effect of gravel-sand mulch on soil water. HYDRUS-1D is a well-known Windows-based computer software package for simulating water, heat, and solute movement in 1-D, variable saturated porous media.

The present study was conducted by combining field experiments with HYDRUS-1D software to quantify the effect of gravel-sand mulch on soil water during the crop growth period. We hope to provide a general idea of the principles and methods of management of the GSMF and the scientific basis for using gravel-sand mulch to improve the soil moisture conditions in the semi-arid loess region of northwest China.

MATERIALS AND METHODS

Study site description

The study area is located in the west of the Loess Plateau (36°17′N, 104°84′E) at an altitude of approximately 1720 m. The climate is semi-arid: mean annual precipitation is about 425 mm, with nearly 70% falling between May and September. Mean annual temperature is 6.3°C, with a maximum average temperature of 15°C and a minimum average temperature of 1.8°C. Average annual pan evaporation is 1526 mm. The soil is a sandy loam of loess origin. The soil profile characteristics are presented in Table 1.

Table 1 The average soil physical characteristics in the experimental plots.

Depth (cm) I	II	Sand %	Silt %	Clay %	Bulk density (g cm^{-3})
0–12	–	Gravel-sand mulch			–
12–32	0–20	13.2	65.9	20.9	1.48
32–52	20–40	11.0	70.6	18.4	1.41
52–72	40–60	9.7	68.7	21.6	1.39
72–120	60–120	8.9	72.5	18.6	1.42

I = Gravel-sand mulch, II = No-mulch. Sand, silt and clay were defined as particles 2.0–0.05, 0.05–0.002 and <0.002 mm in diameter, respectively.

Experimental design

Field experiments were conducted from 4 April 2001, the watermelon planting date, to 12 July 2001, the watermelon harvest date, on two adjacent fields, one with no mulch and the other with gravel-sand mulch. The depth to groundwater is more than 80 m, which is too deep to be used.

The dimensions of the gravel-sand mulch field were 15 m × 8 m. In autumn 1999, deep tillage was conducted, a base-rich fertilizer was applied and then the surface was made smooth and compact. In winter 1999, 12 cm depth of gravel and sand: small gravel ratio of 4% from a nearby river bed, was applied to the surface of the field. A ridge was created around the field to prevent the loss of rainwater. During the experimental period, no irrigation water was applied; the only available water was precipitation. Watermelon has been planted on the field since 2000. On 4 April 2001, watermelon seeds were sown at an in-row spacing of 1.0 m in rows that were 0.6 m apart. A trowel was used to make a small hole (10 cm long, 1.5 cm wide and 2 cm deep) under the mulch, into which two seeds were placed. Then the seeds were covered with wet soil, followed by 2 cm depth of gravel-sand mulch, and finally some coarse sand was placed on the mulch, in order to conserve heat and soil moisture.

The dimensions of the non-mulched control field were 5 m × 8 m. It was also surrounded by a ridge to prevent loss of rainwater and during the experimental period the only water available was precipitation. Corn was grown in this field in 2000. In autumn 2000, deep tillage was conducted and a base-rich fertilizer was applied. On 4 April 2001, watermelon was sown at the same spacing as in the mulched field, but the hole had a depth of 3 cm.

Volumetric soil water content was measured at depths of 12, 30, 50, 80 and 120 cm, from soil cores (outer diameter: 40 mm, inner diameter: 35 mm, length: 20 cm) taken at four randomly selected locations in each field. Soil samples were taken once every 10 days between planting and harvesting and were oven-dried at 105°C for 24 h to determine moisture content.

Numerical modelling

The HYDRUS-1D code (Šimůnek *et al.*, 1998) was used to simulate 1-D vertical water under field conditions. The soil hydraulic properties were modelled using the van Genuchten-Mualem constitutive relationships:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m}, & h < 0 \\ \theta_s, & h \geq 0 \end{cases} \tag{1}$$

$$K(h) = \begin{cases} K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)\right]^2, & h < 0 \\ K_s, & h \geq 0 \end{cases} \tag{2}$$

where

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \; m = 1 - 1/n \tag{3}$$

and θ_s is the saturated water content (cm^3 cm^{-3}), θ_r is the residual water content (cm^3 cm^{-3}), K_s is the saturated hydraulic conductivity (cm day^{-1}) and α, n and l (= 0.5) are the shape parameters. Running the model required the hydraulic parameters θ_s, θ_r, K_s, α and n. The hydraulic parameters were estimated using ROSETTA (Schaap *et al.*, 2001) from soil physical properties measured in the experimental fields (Table 1).

An atmospheric boundary condition was imposed at the soil surface accounting for time-dependent data of precipitation (cm day^{-1}), potential evaporation rate (cm day^{-1}), potential transpiration rate (cm day^{-1}). The daily average potential evapotranspiration rate (cm day^{-1}) ET_p was calculated from weather station data using the FAO-56 Penman-Monteith equation (Allen, 2002). The values of the parameters in Penman-Monteith equation came from Wu *et al.* (2005). ET_p was partitioned between potential evaporation (E_p) from the soil surface, which was calculated by Ritchie's formula (Ritchie, 1972), and potential transpiration (T_p) by plants. Model performance was quantitatively evaluated by calculating the average error (E_m), the root mean square error (RMSE) and the coefficient of residual (C_{RM}) between the measured and simulated water contents, as described by Lü *et al.* (2009).

RESULTS AND DISCUSSION

The simulated and measured values of soil water content at 12, 30, 50 and 80 cm soil depths for both fields during the experimental period from 4 April (the first day of sowing) to 12 July 2001 are shown in Fig. 1. The daily rainfall is shown in Fig. 2. The variation of soil water content follows the variation in rainfall. High precipitation resulted in increased soil water content, especially in the near surface soil layer, as shown in Fig. 1 for both the gravel-sand mulch and bare soil. In the surface layers, water content fluctuated considerably, mainly owing to precipitation, while in the deeper soil layers water content fluctuated less. Although the measured and the simulated water content varied in the same manner over time, in the gravel-sand mulch field the water contents simulated at 12, 30, 120 cm depth were lower than the measured values and C_{RM} was positive in these layers. At 50 and 80 cm depths in this field, the simulated water contents were higher than the measured values and C_{RM} was –0.1103 and –0.1027, respectively. In the non-mulch field, the simulated water contents exceeded the measured values at 12, 30, 80 and 120 cm depth and had negative C_{RM}. At 50 cm depth, the simulated values were lower than the measured values and C_{RM} was 0.1108. On 28 June (the 86th day after sowing), because of continuous and high rainfall, the measured and simulated values all increased rapidly at 12 cm depth. But the result is not obvious at 50 and 80 cm depth.

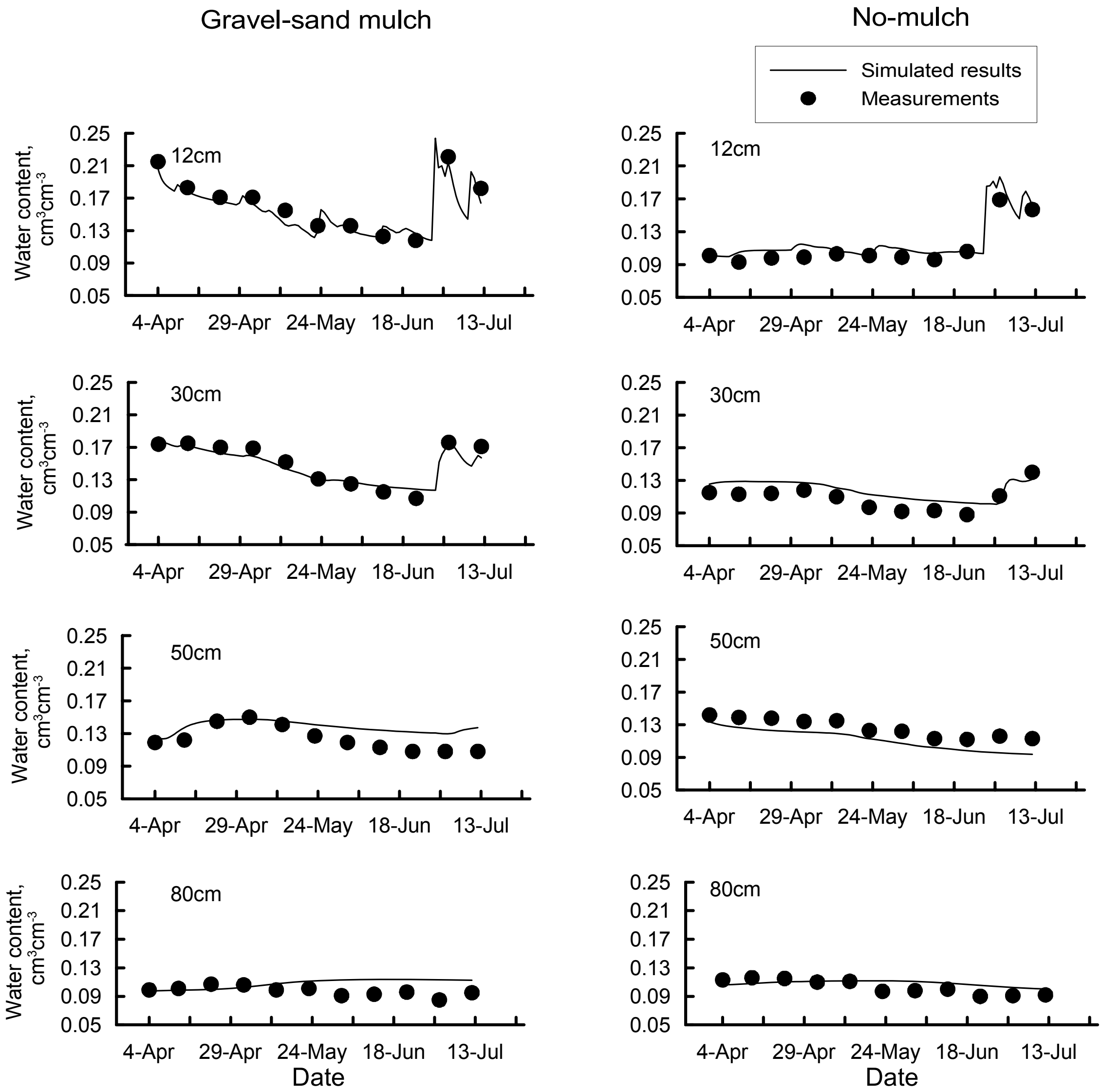

Fig. 1 Observed and simulated water content at 12, 30, 50 and 80 cm depth under the gravel-sand mulch and no-mulch, 4 April–12 July 2001.

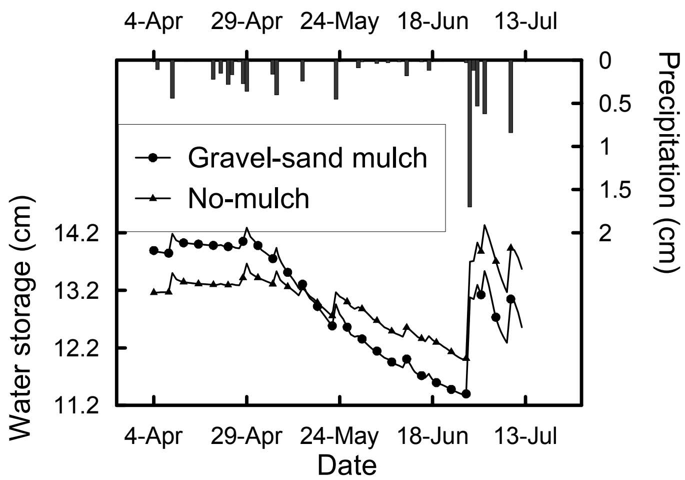

Fig. 2 Measured daily precipitation and simulated water storage of the root zone in the gravel-sand mulch and no-mulch fields, 4 April–12 July 2001.

The discrepancies between the measured and simulated soil water content were generally small: $|E_m| \leq 0.0136$ cm^3 cm^{-3} for gravel-sand mulch and $|E_m| \leq 0.0136$ cm^3 cm^{-3} for no mulch field, and RMSE ≤ 0.0168 for gravel-sand mulch and RMSE ≤ 0.0219 for no mulch field. The difference between measured and simulated soil moisture content was less at the deeper depths (80 and 120 cm) compared to the shallow depths (12 and 30 cm), whilst at 50 cm depth, measured values were higher than simulated values. Possible reasons for the discrepancies between the measured and simulated soil moisture content are that the modelling did not take account of a number of factors, including: soil structure (each of the four soil layers was assumed to be homogeneous), preferential flow in the soil and the precise distribution of plant roots. On the whole, HYDRAUS-1D is successful in simulating the soil moisture movement at the experiment field.

Over the whole watermelon growing season, the total rainfall was low, only 76.5 mm, and one of the largest rainfall events was 17 mm. Therefore the rainfall barely influenced the deeper soil water content as below 80 cm depth, the soil water content in both fields remained similar and constant throughout the watermelon growing season (Fig. 1). The major influence of rainfall on soil water content was above 30 cm depth. At the start of the experiment the soil water contents in the gravel-sand mulch field at 12 and 30 cm depth, respectively, were obviously higher than that in the non-mulch field. This was because during the previous autumn and winter there was no plant growing in the two experimental fields, but the gravel-sand mulch reduced evaporation, conserving soil water compared to the non-mulch field. Therefore, in the initial stage of watermelon growth, there was higher soil water content in the gravel-sand mulch field which was very beneficial to the germination of watermelon. Because the rainfall was so low from 4 April to 28 June 2001, the effect of rainfall on soil water content distribution was very small. During this period, in the non-mulch field, the soil moisture content was low and constant. In contrast, in the gravel-sand mulch field, the higher initial soil moisture content decreased over time due to transpiration and influent seepage at 12 and 30 cm depth. After the large rainfall event on 28 June, the rainwater was rapidly infiltrated into the soil through the gravel-sand mulch (the saturated hydraulic conductivity is 712.8 cm day^{-1}). At 12 cm depth, the soil water content reached 0.2005 cm^3 cm^{-3} in the mulch field and 0.19 cm^3 cm^{-3} in the no mulch field after the rainfall event (28 June). Soil water content in the gravel-sand mulch field at 30 cm depth was also higher than at the same depth in the non-mulch field after the rainfall event. But the rainfall event did not affect the soil water content below 50 cm depth. Since watermelon roots occur mainly in the 12–30 cm soil layer the effect of soil water content on watermelon growth in this layer was particularly important. After a little rain, rainwater can appear at the 12–30 cm depth soil layer and stay at this layer, which is the primary area of root distribution in the mulch field. But the rainwater can only stay at the 0–20 cm depth soil layer in which soil moisture can be rapidly lost by evaporation.

Figure 3 shows the cumulative soil water flux at 12 cm depth for the gravel-sand mulch and no-mulch field. In the no-mulch field, the downwards movement of soil water at 12 cm depth is very small when the rainfall is low. When rainfall is high, infiltration from the surface soil layer (0–12 cm) to the root zone can be seen. In other words, if rainfall is low, most of it is intercepted by the surface soil layer (0–12 cm) and lost by evaporation rather than being available for plants. In the gravel-sand mulch field, the situation was very different. Because the surface soil layer (0–12 cm) is gravel-sand mulch, it has a higher saturated hydraulic conductivity, even if rainfall is low, the soil water content increases rapidly. After larger rainfall events the increase in soil moisture content is even more obvious. Over the entire watermelon growing season the cumulative infiltration flux at 12 cm depth is 5.8 cm for the gravel-sand mulch field and is 2.9 cm for the non-mulch field. This water is stored in the 12–50 cm soil layer, which is where most of the watermelon roots occur Therefore, a higher soil moisture content in this layer may enhance watermelon growth.

Figure 4 shows cumulative daily infiltration, transpiration and evaporation simulated in the gravel-sand mulch field and non-mulch field during the experiment. Gravel-sand mulch at the soil surface clearly affects the soil hydrological processes which involve water storage in the root zone (Fig. 2), transpiration and evaporation (Fig. 4) during the watermelon growing season. Because of

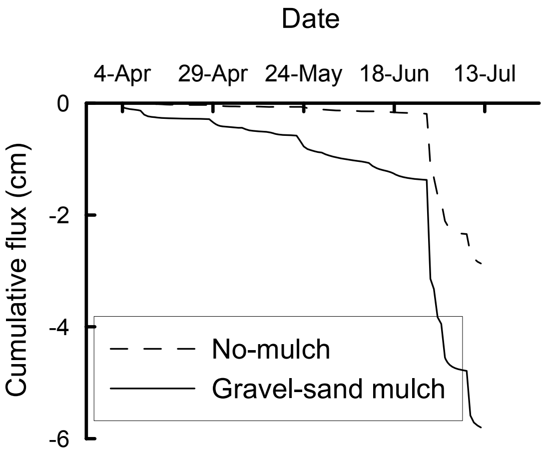

Fig. 3 Cumulative soil water flux at 12 cm depth for the gravel-sand mulch and bare-soil, 4 April–12 July 2001.

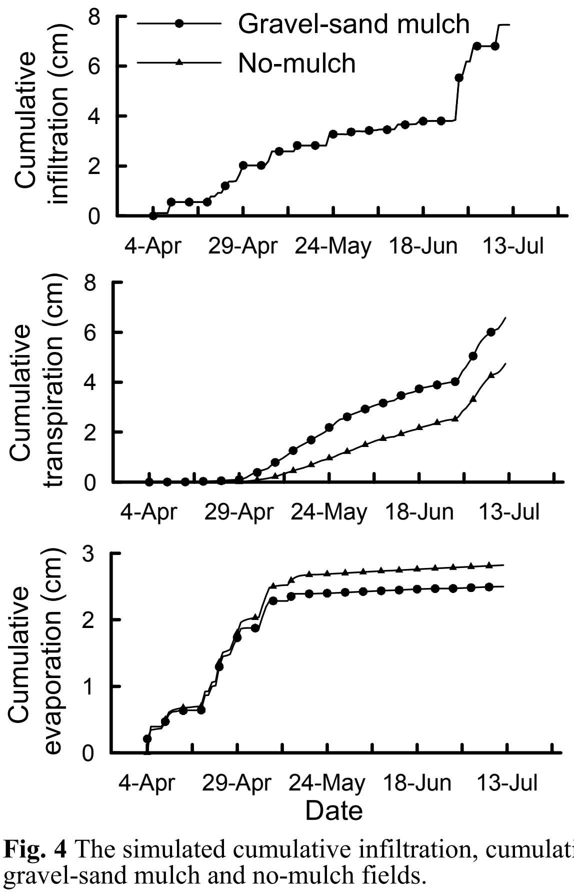

Fig. 4 The simulated cumulative infiltration, cumulative transpiration and cumulative evaporation at the gravel-sand mulch and no-mulch fields.

the low rainfall, the cumulative infiltration at the surface was the same in both the gravel-sand mulch and non-mulch fields for the watermelon growth period. The other reasons for the same cumulative infiltration were that there was a 30-cm high ridge around both of the experimental fields which prevented any water loss through surface runoff, and the interception of rainfall by the crop was not considered.

In the watermelon growing season, several major rainfall events occurred, mainly after 28 June. Therefore, before 28 June the water needed for watermelon growth mainly came from the root zone storage capacity. This period was key for watermelon growth. The water storage of the root zone controlled watermelon transpiration and growth. During the period of 4 April–3 May 2001 (the 30th day after sowing), the water storage capacity in the gravel-sand mulch field was 0.842 cm higher than that in the non-mulch field. This period was the initial stage of watermelon growth, when the main root length was 12–30 cm and the leaf area index was also low, so there was very low transpiration in the two fields and evaporation was similar in both fields at about 1.7 cm (Fig. 4). Because rainfall was low, cumulative infiltration was only about 1.8 cm. Therefore the change of water storage was gentle (Fig. 2). During the period of 3–15 May 2001 (the 40th day after sowing), because of several small rainfall events (cumulative rainfall 1.43 cm), the watermelon grew rapidly and the water storage changed obviously between the gravel-sand mulch field and the non-mulch field. Evaporation form the gravel-sand mulch field was smaller than from the non-mulch field. In the gravel-sand mulch field, the watermelons grew faster and transpiration was significantly greater than in the non-mulch field. On 15 May, the water storage in two fields was similar. After 15 May, watermelon leaves completely covered the soil surface in both fields so that evaporation decreased to zero. The cumulative transpiration increased for the gravel-sand mulch field at a slightly higher rate than that in the non-mulch field. After 28 June 2001, due to several major rainfall events, transpiration increased significantly from both fields.

SUMMARY AND CONCLUSIONS

Experimental and numerical modelling studies of soil water were carried out in a gravel-sand mulch field and a non-mulch field during the watermelon growing season. The simulation results were compared with the measured soil water content at different depths. Statistical criteria used to evaluate the simulated results showed that they were in reasonable agreement with the measurements, although some discrepancies appeared because of the influence of soil texture. For soil water content the average error E_m ranged between –0.014 and 0.0136, the root mean square error RMSE was not greater than 0.0219, and the residual ranged between –0.1296 and 0.1108.

Overall, the HYDRUS-1D model was found to be a useful tool to determine field-scale hydraulic properties by using experimental data for analysing soil moisture under field conditions. The output of the model may provide valuable information for practical applications such as determination of sowing date and application of irrigation.

The results of the study showed that a surface gravel-sand mulch field could provide a more favorable environment for plant growth than a non-mulched field in the semi-arid loess region of northwest China. The results indicated that gravel-sand mulch could beneficially enhance water storage in the soil profile, especially at the time of seed germination. The water storage was 13.9 cm for the gravel-sand mulch and 13.1 for the non-mulch field. Gravel-sand mulch improved the soil hydrological processes. It was effective in reducing evaporation (the cumulative evaporation: 2.9 cm *vs* 2.4 cm), improving transpiration (cumulative transpiration: 6.5 cm *vs* 4.7 cm) and infiltration. This study helps us to better understand the value of such indigenous knowledge and experience, which may need to be combined with modern agriculture technology to maximize its effectiveness.

This study only examined a two-year-old gravel-sand mulch field but assessment of the long-term effects of gravel-sand mulch on soil moisture movement and crop growth requires further studies. According to the local farmers' experience, gravel-sand mulch has been applied to loam soils for 10–50 years. Therefore, overtime desertification may occur as the original loam soil texture is turned into loamy sand or sandy loam. This would result in an increase in hydraulic conductivity, reducing the soil water content of the topsoil and benefits for crop growth. Therefore future study is required of the long-term effect of gravel-sand mulch on crop growth.

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