We thank anonymous reviewer for their constructive comments. The manuscript has been significantly improved by addressing the comments. The following are our point-to-point responses to their comments.

<u>Responses to the Comments from Reviewer #1</u>

1) The author claims that the DSR measurement performed in this study, being a task never reported before. On the other hand, the explanation on the DSR measurement and relevant principles/details were not presented. For example, it is understood a lysimeter installed at the depth of 3.2 meter, to enable the measurement of DSR as being below the deepest root c.a. 100cm. However, the length and width of this lysimeter is only 0.3m*0.3m, while the root distribution can reach a 200cm diameter horizontally. This makes this reviewer questioning the reliability of DSR measurements. Also within the deep soil, the relative humidity is rather hight(e.g., 99.9%), which will lead to vapor condensation on lysimeter device, how this vapor condensation effect is removed also needs some explanations.

Response: Thank you for the comment. The explanation of this new type of Lysimeter has been published in HESS in details before (Cheng et al, 2017), so that is why it is only briefly explained in this article. The conventional Lysimeter uses an impermeable container (constructed all the way from ground surface downward) to wrap the soil column, blocking the horizontal flow of the soil layer, thus there is inevitable water potential difference existing inside and outside the container of the Lysimeter. It is notable that horizontal soil moisture flow in the active root zones in arid and semi-arid regions could be significant as the roots prefer to grow horizontally to intercept the maximum infiltrated water. In arid and semi-arid regions, the roots usually do not grow vertically to great depths because the regional groundwater table is so deep that it is almost impossible for roots to tap groundwater. Below the active root zones, horizontal movement of water moisture will be substantially reduced and vertical movement of water moisture starts to prevail.

The new Lysimeter has an upper water balance part and a lower measurement part which can directly measure the water flux. Specifically, the flux infiltrating into the balance part at the depth of the measurement face should equal the flux exiting the balance part and entering the measurement part. There is no need to build an impervious container to wrap the vegetation tested for the new Lysimeter above the measurement face. The 0.3 m*0.3 m is the planar view size of the new Lysimeter, and the height of the Lysimeter is 1 meters. Because the measurement face of the Lysimeter is at a depth of 2.2 meters, the installation of the instrument requires downward excavation to a depth of 3.2 meters. After this step, lateral excavation will be conducted (under a 2.2 m undisturbed soil) to generate a cave with the size of 0.3 m of width, 0.3 m of length, and 1 m of height to host the Lysimeter. After the installation of the Lysimeter, the excavation will be backfilled using the native soil. The experimental site was flat sandy land before ASK was planted for sand control 40 years ago. After 40 years of development, the region is dominated by ASK, scattered Rhamnus parvifolia, Chenopodium glaucum, Setaria viridis and the field average vegetation coverage has reached 80%. In order to investigate the distribution of the roots of ASK, five ASK plants with the same growth and age were excavated on the adjacent plots of the experimental site to conduct the analysis of roots layer by layer up to 1.2 m below ground surface. The average root of these five ASK plants at a particular depth is regarded as the representative root of ASK plants in this area at that depth.

The condensate of the soil layer in the semi-arid area is indeed an important source, but the groundwater level in this area is about 7 meters deep, so the groundwater replenishment on soil moisture for shallow soil layers less than 2.2 m deep is essentially negligible. Therefore, the source of condensate at a depth of 2.2 meters comes solely from precipitation, and we can still use the water balance principle to calculate the distribution of precipitation-induced infiltration in each soil layer.

2) The author claims that the direct measurement of ET is not reliable, but the current approach deployed to measure DSR combined with water balance equation will give accurate estimation of ET. This is a very strong statement while way beyond the reality. If one looks back the point one about the reliability of DSR measurement in this study.

Response: Implemented. According to the literature review conducted by the authors, the methods of directly measuring ET include Lysimeter, eddy correlation method, Bowen ratio method, Large aperture scintillation method, etc. Taking the most advanced eddy correlation method as an example, the measurement error may be 20% or higher and the required monitoring conditions are quite demanding. Furthermore, it is difficult to avoid the influence of human factors on the experimental results. This study provides an inexpensive measurement method that directly measures the water flux at the lower interface of the target layer (the deep soil recharge or DSR), and combine DSR with a few factors that can be accurately measured in real applications (such as precipitation and soil water storage) to calculate ET from the law of conservation. The deficit of this method is that it measures the ET at the point where the Lysimeter is located, thus it may not be the representative ET value over a large scale. Upscaling of the point ET value to large-scale ET value is an important issue and should not be overlooked in the future.

3) The way the author investigate the soil texture change is too much data-limited (e.g., only one plot, and the averaged mixed information was used), which renders the reliability of relevant analysis.

Response: First of all, we need to point out that this study does not consider the exact spatial distribution of soil size distribution that is often important for conducting a precise unsaturated flow simulation (which is not the focus of this investigation). Instead, the purpose of measuring the soil particle sizes is to estimate the capillary rise based on the "average" grain sizes of sand. The capillary rise height is an important parameter for designing the new Lysimeter (as the height of the balance part of the Lysimeter should be greater than the typical capillary rise height at the site). Secondly, the artificially planted ASK forest land of the experimental plot is relatively homogenous. We selected five pieces of ASK for excavation and collected soil samples layer by layer over the 220cm thick soil profile. To study the changes of soil particle sizes over depth, we mixed the soil of five samples at individual layers and analyzed it to minimize errors caused by one plot sample.

4) There are no any numerical analysis/experiment to investigate/validate relevant hypothesis, which also jeopardized the credibility of this study.

Response: At present, there are many models to study the process of soil infiltration, but there are relatively few measured data for arid and semi-arid sandy lands. The purpose of this study is to use the newly designed Lysimeter to measure the water balance information of precipitation in this special type of land, and to evaluate the deep soil water information of the area through the measurement of DSR. The probes used here are commonly adopted by many other soil scientists and are reliable. It is our intention that such acquired datasets can be eventually utilized in sophisticated numerical modeling of unsaturated zone water dynamics in the future.

Response to other comments in the article

1 line 60, line 75, Citation error

Response: Implemented.

2 line 95, The bottom right picture has glare effect, cannot give readers nice impression on the experimental site. Also, it would be nice to have a UAV image of the study site.

Response: Implemented. We do not have a drone, but we chose a clear picture of the plot instead.

3 line 105-107, This is very confusing. Are you saying you have a groundwater table at 180cm? and 60cm capillary rise is from that 180cm GW table? But you said the region has GW table of 5.3 - 6.8m. This deserves careful consideration and clarification. Studies have shown that the vapor can be transferred to surface from more than 100m deep zone of the sand dune.

Response: The depth of the root layer of Artemisia Ordosica in this area is 120 cm (meaning that water within the 120 cm depth may be transpired through root). Furthermore, the capillary water rise height of the sandy soil in this area is 60 cm (meaning that water may be moved upward a maximum height of 60 cm by the capillary force). Therefore, the maximum uplifting of water through the transpiration of root and capillary rise is the summation of 120 cm and 60 cm, which is 180 cm. In another word, for any water within the 180 cm depth, there is a possibility that it can return to atmosphere (The amount of vapor transmission is small, so it is not considered here); for any water below 180 cm depth, it is impossible for it to return to atmosphere (thorough evapotranspiration) and it can only keep going down to recharge the deep soil, assuming that vertical downward movement of soil moisture below the 180 cm depth is dominating and any horizontal soil moisture movement below the 180 cm depth is secondary and negligible. In this study, considering the possible (but unlikely) small variation of capillary rise because of the (minor) soil particle sizes variation in the space, we further extended the depth of measurement 40cm down to 220cm below ground surface. By doing so, the possibility for water at the depth of 220cm t5.3-6.8 m o return to the atmosphere through evapotranspiration is essentially zero. Above analysis will not be affected by the regional groundwater table which is sufficiently deep.

4 line 140, what is the wet bulk density you are referring to? before and after backfill? Are they close to each other? If not , how will this affect your results?

Response: This paper does not concern the accurate determination of bulk density. The description here is that water is used to wet the soil before excavating the soil profile and installing the Lysimeter to make sure that the sand is relatively compact and will not collapse during the excavation process. When installing the Lysimeter, excavation is conducted outside of the targeted area first to a designated depth and then conducted sideway horizontally, and the Lysimeter is installed under the undamaged soil layer above the Lysimeter. After the Lysimeter is installed, water is also used to wet the soil profile to make sure that the sand is relatively compact. The collected data can be used after the sand has settled naturally for one year to ensure data quality.

5 line150, The dimension/scale is not indicated in the figure. Please do.

Response: Implemented.

6 line 153, well, this deserves more consideration. In Land Surface Model, if you considered most of the physical processes (e.g,. intercepted water by leaf, interception-induced evaporation, through-fall, soil hydrothermal properties etc.) you should be able to estimate infiltration rate and runoff. This is very basic though.

Response: If all factors are taken into consideration, it is indeed possible to predict whether there will be runoff on the surface. However, the reality is that the environmental factors are complex, with large changes in vegetation coverage, precipitation, and soil moisture. This is indeed an important issue to address but further data collection works are needed to make it possible. The research here is based on direct field observations, and the terrain in this area is relatively flat and there is no surface runoff. The focus of this research is to explore the water balance process of precipitation water in unknown environments using a simple and straightforward water balance approach based on direct observation of DSR and other factors.

7 line 254, Do you have measurement of transpiration? I guess you mean root water uptake here? Do you mean all the soil moisture decrease can be attributed to RWUP here?

Response: This study did not separate transpiration from evapotranspiration, and used evapotranspiration to classify plant evaporation and soil transpiration as one category. The reduction in soil water content of each layer here should be the result of root water uptake and soil evaporation. From April 25th to June27th, there were 31 observed precipitation events in total. The maximum precipitation was 18.8 mm, and the minimum precipitation was 0.2 mm. These precipitation events did not change the decreasing trend of soil moisture. This study is incapable of tell whether soil water consumption during this period is transpiration or plant water consumption (root water uptake). However, the soil moisture drops sharply during the germination period. The transpiration intensity of this period is not the largest in an annual basis. The summer soil transpiration intensity is greater but we still observe that precipitation infiltrates to recharge deep soil. Based on this, we speculate that vegetation consumes a great deal of soil water during the germination period, and the specific amount of water consumed needs further and more detailed experimental observations.

8 line 280, Do you have long climatology to be compared with? In order to determine wet, dry and normal.

Response: As shown in line 90 in the text, the precipitation observation data from 1960 to 2010 in this area show that the multiple-year average precipitation is 358.2 mm. When the annual precipitation at a particular year is higher than 358.2 mm, it is considered a wet year; if the annual precipitation at a particular year is lower than 358.2 mm, it is considered a dry year.

9 line 287, This is not correct and not corresponding to the content of this section. Please rephrase. It is more "characteristics of DSR ... ..."

Response: Implemented.

10 line 355, It is more water balance analysis than water distribution.

Response: Implemented.

11 line 460, You mean even only 2mm DSR is enough to sustain the local water demand other than sustaining the local ecosystem itself. It is suggested to explain a bit more details in terms of 'sustainability'. Do you consider plant only here or also local water resources for other use?

Response: The DSR that can enter the 200 cm depth soil layer is the remaining water after the consumption by vegetation. If the DSR is greater than zero, it means that precipitation not only can meet the needs of vegetation growth, but also has excess water that can infiltrate into the deep soil layer. When this is the case, we regard the system as sustainable. Otherwise, if the DSR is reduced to zero, it means that the precipitation is not sufficient for satisfying the consumption of the vegetation, thus is unsustainable.

We thank anonymous reviewer for their constructive comments. The manuscript has been significantly improved by addressing the comments.

Responses to the Comments from Reviewer #2

The Three North Shelterbelts is a huge afforestation program launched in China in the last century, which has made great contributions to regional sand fixation, dust-storm prevention and ecological environment improvement. However, it caused great concerns about hydrological cycle and ecological environment evolution. In this manuscript, the characteristics of water cycle were obtained through the comparative analysis of the observation data of the key parameters in the process of hydrological cycle in the Artamisia sphaerocephala Krasch sand-fixing land in the Three North Shelterbelt area. The basis of this research is the formula (1) in L160, as the evapotranspiration, the manuscript stated "Evapotranspiration is calculated through a water balance equation when precipitation and soil moisture data are collected", how is it calculated? whether the calculation is accurate. Is $P + C_m*d - DSR - E = \pm\triangle W$ ***a soil moisture storage change (should be variation here), what is the physical basis or meaning? W is soil moisture storage, what is this? What form it is***

stored? Since the horizontal growth of shallow roots is concluded, is it reasonable for the Lysmeter not to consider the horizontal soil water transformation? In addition, how many samples of Artamisia sphaerocephala Krasch sand root excavations? How representative is it? Before accepting for publication, all these questions need to be implemented by the authors.

The purpose of this research is to use a newly designed Lysimeter to directly measure the deep soil recharge (DSR) of the ASK plot at the depth of 2m without damaging the in-situ soil layers. Based on the obtained information of DSR at 2 m depth, the change in soil moisture content from the beginning of the experiment to the end of the experiment and precipitation amount, then evapotranspiration can be calculated by using a water balance equation. This is a new method to obtain DSR information at a targeted depth of soil layer based on direct field observation in arid and semi-arid sandy land when the regional water table is sufficiently deep so will not affect the measurement of DSR.

The advantage of this newly designed instrument is that it can be directly installed at a depth of 2 m depth, and there is no need to wrap a soil column like a conventional Lysimeter to block the horizontal flow of soil. There are no outflow rivers and artificial recharge in this area, and precipitation is the only source of water recharge in this area. Considering that 99% of the water consumed by vegetation is evapotranspiration (ET), the residual water remained in plant structure could be ignored.

According to the principle of water balance, precipitation = ET+ the change of soil water storage within 2m + the amount of DSR. Precipitation is measured by a rain gauge, DSR is directly measured by this new type of Lysimeter, and the soil moisture storage within 2 m is obtained by the soil moisture probes to obtain the soil volumetric water content, which is multiplied by the thickness of the soil layer to yield the soil water storage. Therefore, ET can be computed using above water balance equation.

The experimental plot is flat, and the soil is relatively uniform in the horizontal direction, the coverage of the plot reached 80%, the plot is relatively homogeneous, so we can use experimental observation result at a local scale as a surrogate to represent the entire homogeneous area. However, upscaling of the point ET value to the large-scale ET value should be cautious and not overlooked in the future investigations. The new instrument avoids disturbing the soil layer and directly measured the DSR at the soil interface at a depth of 2 m.

In this experiment, five adjacent ASK samples are selected for excavation when collecting the root samples of ASK, and the mean value of the roots of each layer is used for analysis. The purpose of collecting this parameter is to explore the depth of the roots of the ASK and to determine the buried depth of the new Lysimeter. This study provides a new method for measuring the DSR in arid and semi-arid regions, and based on this information, evapotranspiration could be calculated.

Despite the fact that this research is primarily experimental, such experimental works have not been carried out before to investigate the ecohydrological consequence after planting ASK in semi-arid regions and it serves as an important experimental framework of testing soil moisture movement dynamics theories in the future.

The following are our point-to-point responses to their specific comments.

1 L16-all other lines: Why do not use the Eddy Covariance System to measure the near surface evapotranspiration? At least the calculated values should be validated by this observation.

Response: This is a very valuable suggestion that can be incorporated in further investigations. Eddy covariance system is a method of measuring evapotranspiration, and this method is mostly used in large ecological observation stations and is usually quite expensive. Up to present, it has not been implemented in most semi-arid areas of China. In the future, we will conduct a similar experiment near an Eddy covariance system station and compare the data with the Eddy covariance system data.

L72-other lines: The full text should use the passive voice, because characteristics of Artamisia sphaerocephala Krasch are not developed by itself, but formed by environmental forcing.

Response: Implemented. The text has been revised accordingly.

L133: Since the Artamisia sphaerocephala Krasch developed horizontal root, is it too small to excavate a length and width both of 0.3m soil column or design such size of a lysmeter?

Response: Thank you for the comment. The conventional Lysimeter uses an impermeable container (constructed all the way from ground surface downward) to wrap the soil column, blocking the horizontal flow of the soil layer in the root zones(see supply figure A, the conventional Lysimeter; figure B, the new Lysimeter). It is notable that horizontal soil moisture flow in the active root zones in arid and semi-arid regions could be significant as the roots prefer to grow horizontally to intercept the maximum infiltrated water. In arid and semi-arid regions, the roots usually do not grow vertically to great depths because the regional groundwater table is so deep that it is almost impossible for roots to tap groundwater. Below the active root zones, horizontal movement of water moisture will be substantially reduced and vertical movement of water moisture starts to prevail. Meanwhile, if a conventional Lysimeter is used, the vegetation needs to be transplanted into the container, so the soil structure and the vegetation root system will be disturbed. The new Lysimeter of this study is designed to be a small-sized instrument installed at any targeted depth of soil layer below the active root zones in arid and semi-arid regions, without blocking possible horizontal water moisture movement in the active root zones.

The plot selected for the experiment is the artificially restored ASK sand-fixing land. The terrain is widely distributed in the Mu Us sandy land and is relatively flat. ASK is the main vegetation species and the soil types is sandy soil. Under these rather "homogeneous" conditions, the experimental result of selected plot may be representative of the ASK sand-fixing land region. However, we do want to point out that one should be cautious for conducting any upscaling of local value of evapotranspiration to large-scale evapotranspiration value.

The groundwater is deeply buried in the selected plot (around 5.3-6.8 m deep) so the roots of ASK (which is usually less than 1.2 m deep) cannot tap groundwater for water supply. Therefore, precipitation becomes the only water source supply for ASK to grow. In order to maximize the water taking capability, the ASK root system develops horizontally, making the root layer of the plot relatively evenly distributed in a planar view. The other difference from the traditional Lysimeter is that the measuring face of the new Lysimeter is not limited to the ground surface. In fact, this newly designed Lysimeter can be embedded in any depths below the active root zones.

L163: How the DSR is measured or estimated should be specified here

Response: The amount of DSR can be obtained directly through the newly designed Lysimeter, please see (Cheng et al., 2017), also described in this paper, please see line 155-172.

L206: It makes sense to analyze the changes of soil organic matter.

Response: Thank you for the comment. Artificially planted ASK has significantly changed the composition of the soil in the studied area and the distribution of soil organic matter in the top soil. We have tested the organic matter and obtained relevant data for soil layer with the upper 200 cm soil profile, and we will add this new information and analysis in the revised version of this paper. The soil organic matter of the ASK plot is higher than that of the bare sandy land plot at any specific depths within the active root zone. As the depth increases, the soil organic matter of the ASK plot decreases significantly. The soil organic matter content in the 0-20cm depth soil layer is the highest, reaching 1.92g/kg, and the soil organic matter at the depth of 200cm depth soil layer is only 1.5g/kg. The soil organic matter is certainly an important factor, more soil organic matter distribution information will be studied in details when investigating the ecohydrological aspect of the plants in semi-arid regions.

The purpose of this research is to use a newly designed Lysimeter to measure the amount of DSR in order to explore the water balance in arid and semi-arid regions. The soil particle size is measured in this paper for the sole purpose of estimating the height of capillary rise, which will subsequently determine the height of the balance part of the new Lysimeter.

L240: How to physically define the thawing recharge period, germination consumption period, rain season recharge period and plant dormancy period and the frozen soil periodïij§

Response: Thank you for the comment. In this study area, the freeze-thaw period refers to the topsoil (2 meters depth) from the beginning of freezing to the complete melting of the frozen soil (from October to April). The germination period begins from the end of freeze-thaw period to the period when branches of ASK are enlarged, and one or two new leaves start to grow (from April to June). The rainy season refers to a period of relatively concentrated precipitation experienced after the germination period of ASK plot in this region (from June to October). The analysis of the soil water replenishment in the freeze-thaw period, the germination period and the rainy season in this area helps illustrate the replenishment characteristics and water sources of soil moisture and DSR at different times. We will add references to show soil temperature information based on other studies which have reported soil temperature monitoring experiments in similar plots like this study.

Figure 3 should show the soil temperature curve to identify whether it is soil thawing period.

Response: We have designed a double-tube apparatus to measure the depth of the freeze-thaw layer depth. The double-tube apparatus consists of a hollow barrel with a vent hole and a rubber tube inside the barrel. First, the hollow barrel with the vent hole is buried vertically in the experimental plot. The upper level of the barrel is at the ground surface and the length of the barrel is 200 cm. The rubber tube filled with water is placed in the cylinder, and it will be extracted at 8PM daily to record the soil frozen state and the frozen depth, which can be used to interpret the thickness of the frozen soil at that moment. This method can observe the thickness of frozen soil layer, but no soil temperature curve.

L504: What is "sufficient precision" means? I'm sure that 2.33 will be changed with a different "sufficient precision".

Response: Thank you for the comment, the sufficient precision should be changed to wet year. The wet year means that the precipitation amount of this year is higher than the multi-year average precipitation amount. In 2016, the annual precipitation amount is greater than the multi-year average precipitation amount, so it is regarded as a wet year. Under the conditions of wet year precipitation, the infiltration rate of bare sandy land is 2.33 times of that of the ASK land.

New measures of deep soil water recharge during vegetation restoration process in semi-arid regions of northern China

Yiben Cheng[1,4*], Wenbin Yang[23], Hongbin Zhan[32], Qunou Jiang[1,4], Yunqi Wang[1,4*], Mingchang Shi[1]

[1]School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China

[2] Institute of desertification control, Chinese Academy of Forestry, Beijing, 100093, China

[3] Department of Geology & Geophysics, Texas A&M University, College Station, TX 77843-3115, USA.

[4]Jinyun Forest Ecosystem Research Station, School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, PR China

Corresponding Author:

Yiben Cheng (chengyiben@bjfu.edu.cn), Yunqi Wang (wangyunqi@bjfu.edu.cn),

Formatted: Font: (Asian) +Body Asian (等线), 12 pt

Formatted: Space Before: 1 line, Line spacing: Double

Formatted: Line spacing: Double

Abstract

Desertification in semi-arid regions is currently a global environmental and societal problem. This research attempts to understand whether a 40-year-old rain-feed Artamisia sphaerocephala Krasch sand-fixing land in Three North Shelterbelt Program (3NSP) of China can be developed sustainably or not, using a newly designed lysimeter to monitor the precipitation-induced deep soil recharge (DSR) at 220 cm depth. Evapotranspiration is calculated through a water balance equation when precipitation and soil moisture data are collected. Comparison of soil particle sizes and soil moisture distributions in artificial sand-fixing land and neighboring bare land is made to assess the impact of sand-fixing reforestation. Results show that such a sand-fixing reforestation results in a root system being mainly developed in the horizontal direction and the changed soil particle distribution. Specifically, the sandy soil with 50.53% medium sand has been transformed into a sandy soil with 68.53% fine sand. Within the Artamisia sphaerocephala Krasch sand-fixing experimental area, the DSR values in bare sand plot and Artamisia sphaerocephala Krasch plot are respectively 283.6 mm and 90.6 mm in wet years, reflecting a difference of more than three times. The deep soil layer moisture in semi-arid sandy land is largely replenished by precipitation-induced infiltration. The DSR values of bare sandy land plot and Artamisia sphaerocephala Krasch plot are respectively 51.6 mm and 2 mm in dry years, a difference of more than 25 times. The proportions of DSR reduced by Artamisia sphaerocephala Krasch is 68.06% and 96.12% in wet and dry years, respectively. This research shows that Artamisia sphaerocephala Krasch in semi-arid region can continue to grow and has the capacity of fixing sand. It consumes a large amount of precipitated water, and reduces the amount of DSR considerably.

Keywords: Semi-arid land, Artamisia sphaerocephala Krasch, rain-feed vegetation, replantation, infiltration, 3NSP

Formatted: Line spacing: Double

1. Introduction

Desertification is currently a global environmental and societal concern (Reynolds et al., 2007b). Arid region covers about 41% of the Earth's surface, and supports more than 38% of the world's population. 20% of these areas have experienced serious land degradation, which is expected to affect the survival of 250 million people (Reynolds et al., 2007a;Dregne and Chou, 1992;D'Odorico et al., 2013). In 1992, the United Nations adopted the International Convention to Combat Desertification in order to focus on desertification issues (Bestelmeyer et al., 2015). With no exception, China is also facing severe desertification problems (Liu and Diamond, 2005). Up to 2010, the total desertification area in China is 2,623,700 km^2, which is 27.33% of the country's entire land area. Among this, the arid region desertification area is 1,158,600 km^2 (44.16% of the total desertification area of China), the semi-arid region desertification area is 971,600 km^2 (37.03% of the total desertification area of China), and the sub-humid arid region desertification area is 493,500 km^2 (18.81% of the total desertification area of China). To battle desertification, an effective prevention and control measure is to build shelterbelts, using artificial sand-fixing vegetation (Tao, 2014).

The Three North Shelterbelt Program (3NSP), a reforestation program initiated in 1978 in Northeast, Northwest, and North China is the largest shelterbelt project in China (Wang et al., 2004;Wang et al., 2010b). It has been constructed for 40 years, and plays a key role for desertification prevention in Northeast, Northwest, and North China (Li et al., 2004). The shelterbelts of 3NSP have slowed down, halted, and even reversed the desertification process in Northern China (Zha and Gao, 1997;Wang et al., 2012). According to NASA's latest observations, the restoration of vegetation has shown some signs of reversing the trend of desertification in China, accounting for a quarter of the Earth's new green areas (Chen et al., 2019).

It is unquestionable that the implementation of 3NSP in China has reduced aeolian erosion, and improved the overall living environment in the impacted regions (Hanjie and Hao, 2003). However, it is undeniable that the poor choices of vegetation species in some areas of 3NSP has resulted in consumption of a large amount of water resources, causing shortage of water supply to meet other needs, thus threatening the sustainable development of the regions (Wang et al., 2010a). Furthermore, a high planting density in some areas resulted in the death and/or malfunction of a large number of trees (Duan et al., 2011). In contrast, shrubs and herb sand-fixing vegetation appear to grow healthily, thus receive great interests to become proper choices of vegetation species for desertification prevention (Tao, 2014). The infiltration process is also closely related to the development of plant roots, while the distribution depth and development direction of roots in the soil are related to precipitation infiltration (Fan et al., 2017).

To understand the impact of afforestation to the ecohydrological system, thus to assess the long-term sustainability, especially after vegetation reconstruction. Soil water is the most important factor in this system, thus we need to know how the soil moisture changes in these area(Cheng et al., 2020). Evapotranspiration (ET) is also an important ecological indicator in semi-arid regions, and the methods of directly measuring ET include Lysimeter, Eddy correlation method, Bowen ratio method, Large aperture scintillation method, etc. (Billesbach and Meteorology, 2011;Maes et al., 2019). Taking the most advanced Eddy correlation method as an example, the measurement error may be 20% or higher and the required monitoring conditions are quite demanding (Burba and Anderson, 2010). Furthermore, it is difficult to avoid the influence of human factors on the experimental results. In this research, we try to quantify the ET experimentally in a typical semi-arid area in 3NSP through the use of a newly developed Lysimeter. *Artamisia sphaerocephala Krasch* (ASK) is a unique Chinese native sand-fixing shrub plant with strong adaptability (Wang et al., 2013). ASK sand-fixing land

Formatted: Font: Italic

developed on top of bare sandy land has increased evapotranspiration. Meanwhile, because of the form of an organic-rick biofilm commonly seen in ASK forest, the near surface soil permeability has been reduced (Su and lin Zhao, 2003). This will reduce the soil infiltration capacity, resulting in the concentration of soil moisture in shallow soils, and reducing the replenishment of soil moisture in deep soils. In order to understand the soil moisture variation and deep soil recharge (DSR) changes resulted from ASK sand-fixing forest, this research choose a 40-year-old ASK sand-fixing land as the experimental site and use a newly designed Lysimeter directly measure the DSR. We have also conducted a comparative research using a bare sandy land 400 m away from the ASK sand-fixing land site. This research focuses on monitoring precipitation-induced infiltration, soil moisture distribution, and DSR changes in ASK sand-fixing land, then calculate the ET on a small scale according to the principle of water balance. We try to answer the following questions through in-situ measured result: 1) How much influence does vegetation reconstruction have on precipitation infiltration and DSR? 2) Is this kind of vegetation reconstruction sustainable in north China?.

2. Material and Methods

2.1 Research area description

Figure 1 shows the research site which is located in Ejin Horo Banner, on the Eastern margin of Mu Us Sandy Land in the Ordos basin of China, with a geographic location of 39°05’02.8 N, 109°35’37.9 E, and an altitude of 1303 m above mean sea level (m.s.l.). The groundwater table between sand dunes are 5.3-6.8 m below ground surface. The climate is within the semi-arid continental monsoon climate zone. Annual precipitation concentrates from July to September and is highly sporadic. The average annual precipitation from 1960 to 2010 is 358.2 mm (Li et al., 2009). The average annual temperature of this area is 6.5℃, with about 151 days of frost-free season, and the lowest temperature is -31.4 ℃. The average annual potential evapotranspiration is 1809 mm, the average annual sunshine is 2900 hours, and the average annual wind speed is 3.24 m/s. The research area is located in relatively gentle mobile dunes, and the soil type is aeolian sandy soil (Liu et al., 2015).

The experimental site was flat sandy land before ASK was planted for sand control 40 years ago. After 40 years of development, the region is dominated by ASK, scattered Rhamnus parvifolia, Chenopodium glaucum, Setaria viridis and the field average vegetation coverage has reached 80%. The site is relatively homogeneous in terms of soil sand particle distribution so we ~~can~~may use ~~one point~~ experimental observation result at a local scale as a surrogate to represent the entire homogeneous site. However, upscaling of the localized results of this study to large-scale results has not been done in this study and should be investigated in the future when large-scale measurements can be done accurately.

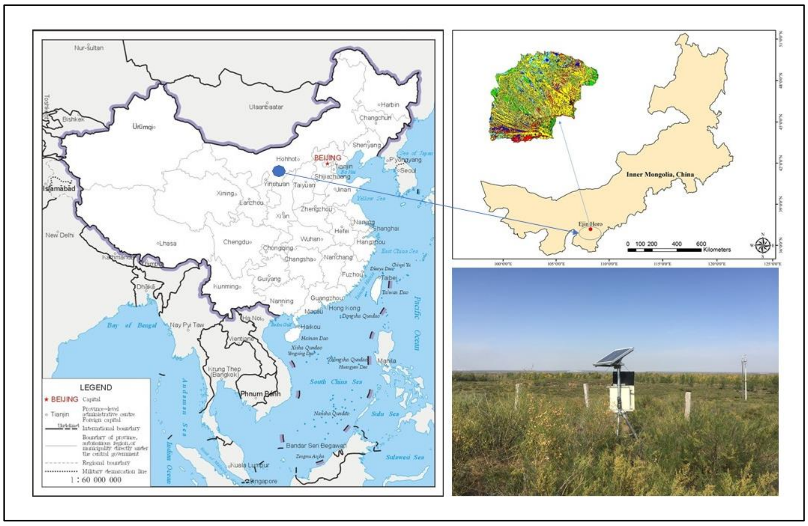


Figure 1~~1~~. Overlook of the experimental field.

2.2 Experimental design

2.2.1 Root system distribution survey, soil moisture and DSR monitoring

Formatted: Font: 9 pt
Formatted: Line spacing: single
Formatted: Font: 9 pt
Formatted: Font: 9 pt

This research chooses five ASK plants with similar heights and crown widths, in which the heights are around 60 cm above the ground. Using the whole root system excavation method, the plant soil is excavated layer by layer with a 20 cm vertical interval, until there are no observable roots. As the deepest root is at a depth of 120 cm (the root system will be discussed in details later in this section), thus the deepest soil moisture that the plant can utilize is 180 cm (120 cm root depth plus 60 cm capillary rise, where the capillary rise is calculated based on the soil texture from experimental plot) (Cheng et al., 2017). The 180 cm depth can be regarded as the maximal depth of evapotranspiration. A new lysimeter is used to measure the deep infiltration, or deep soil recharge (DSR) at a depth of 220 cm (to avoid root water absorption), 40 cm below the maximal depth of surface evapotranspiration. The newly designed lysimeter is improved on the basis of the traditional lysimeter, but it has a reduced size and a new water balance part to improve the measurement accuracy. As shown in the Figure 2, the measurement surface is transferred from the soil surface to soil layer at any designated depth. The detailed explanation of such a lysimeter has been documented in a previous research of Cheng et al. (2017) and will not be repeated here. To understand the soil condition in the research site, the sandy soil samples are collected using a ring cut method, layer by layer with a 20 cm vertical interval, until reaching a 220 cm depth. Soil samples from five ASK plots were collected and mixed together, and sSoil particle size distribution measurements are conducted using a laser particle size analyzer (Mastersizer 2000, Malver, U.K.). We use EC-5 soil moisture probe to measure every 20 cm soil layer of the first 100 cm depth, and every 40 cm soil after the first 100 cm depth until reaching 220 cm depth. The reason of doing so is because the shallow soil layer has roots thus is monitored more closely while the deep soil is relatively uniform and has less roots, thus can be monitored more sparsely.

To study the soil water dynamics of ASK plot, we selected a typical ASK plot in the Mu Us Sandy Land and an adjacent bare sandy plot as a comparison study to quantify the differences in the characteristics of soil water dynamics in bare sandy plot and ASK plot. The experimental design is shown in Fig.2, Fig.3 and explained sequentially as follows.

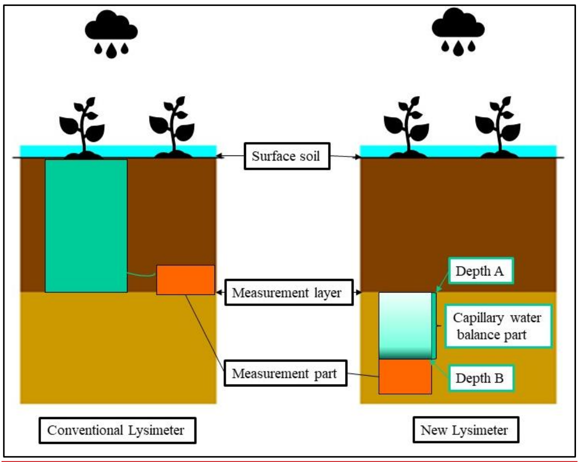


Figure 2 Schematic diagram of conventional Lysimeter and new designed Lysimeter.

The conventional Lysimeter uses an impermeable container (constructed all the way from ground surface downward) to wrap the soil column, blocking the horizontal flow of the soil layer in the root zones. Meanwhile, if a conventional Lysimeter is used, the vegetation needs to be transplanted into the container, so the soil structure and the vegetation root system will be disturbed. If the roots of the vegetation are too long, it is impossible to measure the DSR with a conventional Lysimeter. The new Lysimeter has an upper water balance part and a lower measurement part which can directly measure the water flux (Cheng et al., 2017b;Cheng et al., 2018b). The height of the balance part is equal to the capillary water rising height of this sandy soil. After irrigation and standing still, the balance part will reach~~es~~ a balanced state that the soil at the bottom is saturated, and the top is the highest distance that the capillary water can rise. Specifically, the flux infiltrating into the balance part at the depth of the measurement face should equal the flux exiting the balance part and entering the measurement part. There is no need to build an impervious container to wrap the vegetation tested for the new Lysimeter

Formatted: Keep with next

Formatted: Font: (Default) Times New Roman, Not Italic, Font color: Auto

Formatted: Font: (Default) Times New Roman, Not Italic, Font color: Auto

Formatted: Font: (Default) Times New Roman, Not Italic, Font color: Auto

Formatted: Caption, Centered, Indent: First line: 0 ch, Line spacing: single above the measurement face. The plot is relatively homogeneous, so we can use localized ~~one point~~ experimental observation result as a surrogate to represent the entire homogeneous field. The conventional lysimeter can measures the DSR of a plant, but the new lysimeter measures the DSR of a certain soil layer. For a relatively uniform plot, this measured DSR would be more accurate.

In order to minimize the disturbance of the original soil structure, we need to water both plots in advance before installing the instruments. Firstly, w~~W~~atering the soil in the test area makes the relatively dry sandy soil stable and easy to excavate, as the native dry sandy soil is relatively loose. Secondly, after watering the ASK plot, we start to excavate a soil profile vertically downward at a distance of 1 meter from the main branch of ASK, reaching a depth of 3.2 meters. After this, at the depth of 3.2 meters, we excavate horizontally toward the location of the main branch of ASK to a distance about 1.3 m. Eventually, a body with a height of 1 m, a length and width both of 0.3 m is excavated to install the lysimeter right below the main branch of ASK. By doing so, the distance from the ground surface to the top of lysimeter is 220 cm, and the root system (which is less than 220 cm deep) will not be disturbed. Meanwhile, as the plot has been watered to make the soil stable, no collapse of soil has occurred during the installation of the lysimeter. Thirdly, after putting the lysimeter in place, we use in-situ soil to backfill. During this process, one needs to continuously water each layer of backfill to ensure that the soil is relatively compact. For the installation of lysimeter in the bare sand plot, it is straightforward as one does not need to worry about the disturbance of integrity of the root system. For such a plot, as shown in Fig.3 one can water the soil first, then excavate a square of 1 meter by 0.3 meters to a depth of 3.2 meters to install the lysimeter. After the installation of lysimeter, one can backfill using native soil, making sure to continuously water each layer of backfill to ensure the soil compaction. Soil moisture probes are installed at different depths for both plots. Finally, wait for the watered plots to stabilize to its pre-

Formatted: Space Before: 1 line

excavation status, since pre-watered sandy plot and excavated sand layer will take six months to settle down and meet the requirements of the experiment. Then one can start the experiments. There is a notable limitation of this new lysimeter that should be improved in the future. When measuring DSR, a gauge with a measurement accuracy of 0.2 mm was used to automatically record the amount of DSR. The measuring mechanism of this gauge was that when the accumulated amount of DSR reached a certain amount (0.2 mm), which is the downward volumetric flux over a unit area over a certain time lapse, then a data point will be recorded. When the amount of DSR is large or there is continuous DSR, there will be no measurement problem, but when DSR is very small (less than 0.2mm), it is impossible to know precisely the DSR variation over that time lapse. In the future, we need a more sensitive measuring apparatus that can precisely record the DSR variation with time in a higher precision.

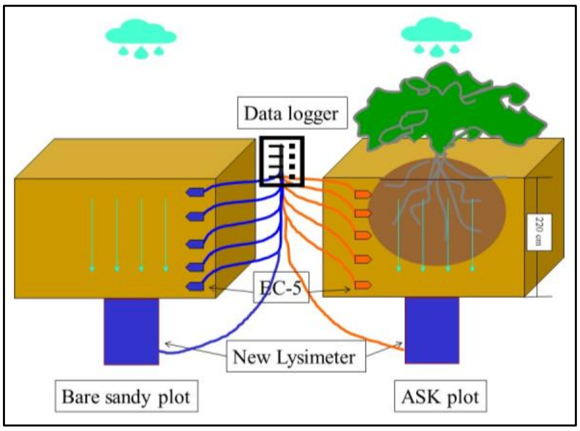


Figure 32. Design of Precipitation-DSR observation site

Formatted: Font: 9 pt

Formatted: Line spacing: single

Formatted: Font: (Default) Times New Roman, 9 pt, Not Italic

2.2.2 Water balance of rain-fed ASK forest land

When precipitation reaches ground surface in semi-arid sandy land, the infiltration rate is usually unpredictable, it may evaporate or run away, or infiltrate. Years of observation records in the area show no occurrence of surface runoff. The water infiltrating into the soil goes through a redistribution process. Part of it is absorbed and utilized by plants' root system, and part of it is stored in soils as soil moisture. The rest will infiltrate passing the maximal depth of evapotranspiration depth and eventually recharges the groundwater system. This research uses the following water balance method to calculate moisture distribution at different depths:

$$P + C_m*d – DSR – E = ±\triangle W \qquad (1)$$

where P is annual precipitation (mm) measured by a rain gauge as the volume per unit square meters, C_m is soil volumetric moisture content (m^3/m^3), d is soil column depth to be measured (mm), DSR is annual deep soil recharge (mm), measured by the newly designed lysimeter as the volume per unit square meters, E is annual evapotranspiration (mm) which is the volume of water lost to the atmosphere due to evapotranspiration per square meters, and $\triangle W$ is the annual soil moisture storage change per unit square meters (mm).

3. Results

3.1 Root system distribution

This research selects representative plants and excavate the soil profile to research the ASK root system growth range. The results show that the ASK root system distribution is umbrella-shaped, as shown in Table 1. The root system distribution range mainly concentrates within 0-60 cm depth, and can reach as deep as 120 cm. The main root grows through the entire depth. The lateral roots are distributed around the main root and can reach a 200 cm diameter horizontally. The density of lateral roots gradually decreases when moving away from the central main root. The lateral roots mainly concentrate within depths of 20-60 cm. From ground surface to a depth of 40 cm, the root system gradually increases, and reaches the maximum density at the 40 cm depth. The dry weight of root between 20-40 cm layer is 51.77% of the weight of the entire root system. The root system gradually decreases after depths of 40 cm, with the deepest root system depth of 120 cm. The results show that the ASK root system in this area is mainly developed in the horizontal direction, which confirms that rainfall is the main water supply for plants in the Mu Us Sandy Land. This conclusion is based on the following reasons. The root development of plans is closely dependent on the source of water supply for the root system, and there are generally two sources of supply: a) rainfall-induced downward infiltration and b) uptake of groundwater from the underneath soil and aquifer. If the primary source of supply for the ASK root system comes from the deep groundwater table, then the root prefers to grow vertically in order to access the underneath groundwater. On the other hand, if the primary source of supply for the root system comes from the rainfall-induced infiltration, the root system prefers to grow horizontally to maximize the intercept of such infiltrated water, and the field observation results confirm that this is the case in Mu Us Sandy Land.

Table 1. Root distribution of the ASK in the vertical direction

Excavation depth(cm)	Root dry matter content (g)	The dry matter accounts for the weight ratio of the whole root system (%)
0-20	21.85	13.26
20-40	85.32	51.77
40-60	30.56	18.54
60-80	14.86	9.02
80-100	8.57	5.2
100-120	3.64	2.21

3.2 Effect of ASK on soil development

There are many factors that affect the soil particle size, including soil crust, vegetation root secrete acidic substances to decompose the parent material, ionic strength, flow rate and surface vegetation fixed sand dust (Yan et al., 2013;Yu et al., 2013;Zhang et al., 2011). The soil particle size of each layer is also different. It is necessary to analyze each soil layer one by one and it is not easy to see the main affecting factors. In this research, to understand the impact of ASK on the local soil, the ASK soil samples and bare land soil samples are collected and sorted based on U.S. Department of Agriculture's soil particle size grading scheme, we collected samples of every 20 cm depth and mixed them together, treated the entire 220 cm thick soil layer each as a homogenized system.

The soil particle size distribution was measured using the MS2000 soil particle size analyzer produced by Malvern, UK. Samples need to be pretreated before the experiment. All soil samples have passed through a 2 mm soil sieve, added 30% H_2O_2 solution to remove organic matter (including biological crust) from the sample, then add NaHMP solution to fully dissolved, and shake 30 seconds to destroy the microaggregate structure of the soil particles.

Table 2 shows the particle size distributions in both the ASK plot and bare sandy plot. Overall, in ASK plot, the medium sand is 19.26%, the fine sand is 68.53%, the very fine sand (or powder sand) is 9.35%, and silt is 2.86%. The soil particle size distributions of the bare sandy plot are as follows. The coarse sand is 3.23%, the medium sand is 50.53%, the fine sand is 36.06%, the very fine soil is 7.19%, and the silt is 2.99%. Comparing the results in ASK plot and bare sandy plot, one can see that the main soil type in the ASK plot is fine sand (68.53%), and the main soil types in bare sandy plot is medium (50.53%) and fine sands (36.06%). Another notable point is that there is 3.23% of coarse sand in the bare sandy plot, but no coarse sand in the ASK plot.

There are clear evidences that the sand-fixing vegetation changes the particle size distribution of the soil (Fearnehough et al., 1998;Pei et al., 2008). A few possible reasons may be responsible for such a change. First, the fine-sand in the 220 cm-thick soil of the bare sandy land is easily removed or eroded from its original position under the force of wind, which initiates sand movement both horizontally and vertically (as suspended particles carrying away by wind), consequently the content of fine sand in the bare sandy land decreases, and the soil structure continuously coarsens. In contrast to this, the content of fine particle in the ASK plot is significantly higher than that in the bare sand. This is largely due to the presence of vegetation in the ASK plot which has substantially subdued the eroding force of wind. In another word, ASK essentially protects the fine sands in the soil to be removed or eroded by wind force. This observation is direct evidence showing that vegetation has a positive role in improving soil particle size composition by maintaining the fine sand particles in the plot. However, one must also be aware that such a change of particle size distribution is a consequence of a complex interplay of aerodynamic force, sand mass movement mechanics, and root-soil interaction force, which are not completely understood up to now and needs further investigation. In summary, the sand-fixing vegetation in northern China not only fixes the sand, but also greatly improves the soil texture.

Table 2. The distribution of soil particle size in research site

Particle size distribution	Extra coarse sand	Coarse sand	Middle sand	Find sand	Very fine sand	Silt sand
Diameter range (mm)	>1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	<0.05
ASK plot	0.00	0.00	19.26	68.53	9.35	2.86
Bare sandy plot	0.00	3.23	50.53	36.06	7.19	2.99

3.3 Annual soil moisture variation of rainfed ASK plot

The experimental area is located in Northern China, with more than three months of intermittent frozen soil period in winter. Multi-year observations show that the frozen soil period is from December of the previous year to March of the following year. The annual soil moisture variation in 2015 is shown in Figure 3. According to the change of soil volumetric water content and the influence of precipitation, the whole year is divided into five stages, which are the thawing recharge period, germination consumption period, rain season recharge period and plant dormancy period .(Tthe freeze-thaw period refers to the top soil (2 meters depth) from the beginning of freezing to the complete melting of the frozen soil. The germination period begins from the end of freeze-thaw period to the period when branches of ASK are enlarged, and one or two new leaves start to grow. The rainy season refers to a period of relatively concentrated precipitation experienced after the germination period of ASK plot in this region. the frozen soil period is not shown in Figure 43). From 2015 to 2018, the trend of soil moisture is basically the same, only the time of the rainy season and the amount of annual precipitation are different.

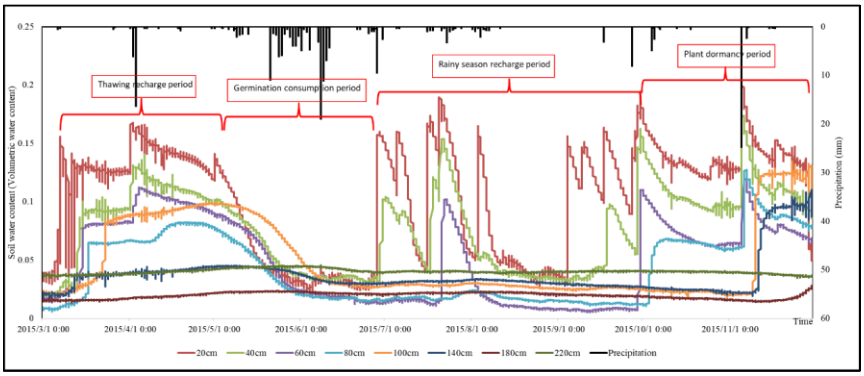


Figure 3 4 Daily soil water content distribution of ASK plot in 2015.

Formatted: Font: 9 pt

Formatted: Space After: 10 pt

After March 6th, the melting snow in ground surface leads to increased soil moisture contents. Around this time, ASK is still in winter dormancy, and does not absorb soil moisture. As shown in Figure 34, from March 6th to May 5th, soil moisture increases significantly. Soil moisture resulted from melting snow can infiltrate into depths of 100 cm to 140 cm. After April 25th, ASK starts germination, and soil moisture gradually decreases. From April 25th to June 27th, there are 31 observed precipitation events in total. The maximum precipitation is 18.8 mm, and the minimum precipitation is 0.2 mm. However, these precipitation events did not change the decreasing trend of soil moisture. This means that during the germination and early growth periods, the moisture absorbing capacity of the ASK root system is extremely high. There is a 9.4 mm precipitation event on June 28th, and the infiltration associated with this event can reach a depth of 20 cm. This means that the growth of ASK starts to slow down around this time, and the shallow soil moisture starts to increase. In October, temperature drops and ASK starts to enter winter dormancy. There is a 4.2 mm precipitation event on October 4th, and the infiltration associated with this event can reach a depth of 60 cm. There is a 24.6 mm precipitation event on November 7th, and the infiltration associated with this event can reach a depth of 140 cm. Soil moisture at 220 cm depth changes very mildly. The results show that though DSR occurs in all seasons, especially during freeze-thaw period, due to vegetation consumption, the amount of DSR is relatively small.

3.4 Effects of annual precipitation on soil moisture and DSR

3.4.1 Comparison of DSR on rain-feed ASK land and bare sandy land

For deep soil moisture variation and distribution, this research uses a newly designed lysimeter to measure DSR on-site (Cheng et al., 2017). The soil layer may be disturbed after the instrument is installed in 2015, so the 2015 precipitation-infiltration data are not used in this study. Results are shown in Table 3. From 2016-2018, the precipitations of bare sandy land are 464.8 mm, 313.4 mm, 245.2 mm, and DSR are 283.6 mm, 67.6 mm, 51.6 mm, respectively. The ratios of DSR to annual precipitation are 60.02%, 21.57%, 21.04%, respectively. The experimental plot of Artamisia is less than 100 m away from the bare sandy land plot, the annual precipitation is basically the same, and DSR values are 90.6 mm, 31.2 mm, 2 mm, respectively. The ratios of DSR to annual precipitation are 19.49%, 9.96%, 0.82%, respectively. According to above data, DSR of the bare sandy land is obviously higher than the Artamisia plot. On Artamisia plot, the interception of the aboveground vegetation, root absorption, evapotranspiration consumes a large amount of water resources, which affects the production of DSR.

When the annual precipitation at a particular year is higher than 358.2 mm, it is considered a wet year; if the annual precipitation at a particular year is lower than 358.2 mm, it is considered a dry year. As shown in Table 3, 2016 is a wet year, 2017 is a normal year, and 2018 is a dry year. In the wet year, the deep soil moistures of the two experimental sites were greatly supplemented, and the effect of bare sand was more obvious. The amount of DSR in the dry years is significantly reduced on both plots, especially in the Artamisia plot, from 90.6 mm in wet years to 2 mm in dry year. Based on these, one can conclude that in semi-arid areas, though vegetation cover can fix mobile sand dunes, it consumes a lot of water resource. Bare sandy land can transport large amounts of water resource to shallow groundwater.

Table 3. Comparative of precipitation and DSR in ASK land and bare sand field

Year	Field type	Precipitation (mm)	DSR (mm)	D/P (%)
2016	Bare sand plot	464.8	283.6	60.02
	ASK plot	464.8	90.6	19.49
2017	Bare sand plot	313.4	67.6	21.57
	ASK plot	313.4	31.2	9.96
2018	Bare sand plot	245.2	51.6	21.04
	ASK plot	245.2	2	0.82

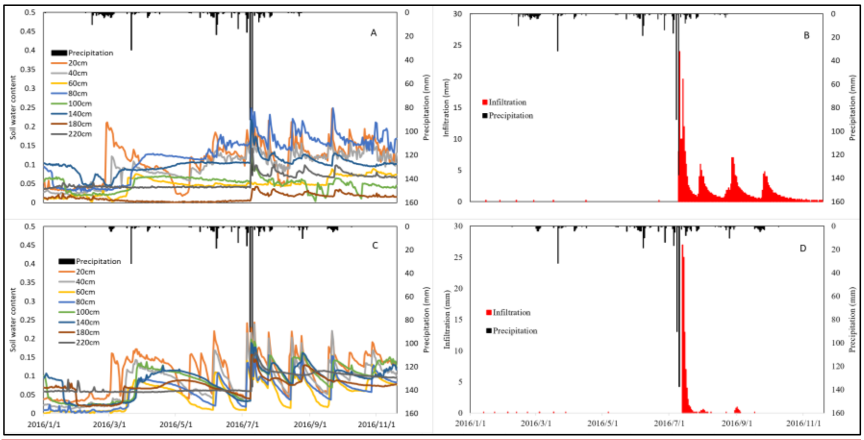
3.4.2 Precipitation response to soil moisture and DSR on two experiment plots

The relationship between precipitation and soil moisture content fluctuations and DSR in 2016 is shown in Figure ~~4~~5 (ABCD). There are 84 precipitation events throughout the year in 2016, with the maximum precipitation amount of 137.2 mm/d happened on July 10th. According to local weather station data, this is the second largest daily precipitation since 1950, and the minimum precipitation amount of 0.2 mm/d happened 11 times throughout the year.

Formatted: Indent: First line: 0 cm, Space Before: 0 pt

Formatted: Indent: Left: 0.63 cm

On bare sandy land, there are 138 infiltration events throughout the year in 2016, with the maximum DSR amount of 24 mm/d, happened on July 11th, and the minimum DSR amount of 0.2 mm/d happened 25 times throughout the year. On ASK plot, there are 42 infiltration events throughout the year in 2016, with the maximum DSR amount of 27 mm/d, happened on July 13th, and the minimum DSR amount of 0.2 mm/d happened 22 times throughout the year. The comparison of these two sets of DSR data shows that ASK can substantially reduce the soil moisture infiltration, DSR of Artamisia plot is reduced by 68.05% compared to bare sandy plot. Heavy precipitation completely wets the entire soil layer and forming a moisture transport channel that facilitates the transport of moisture throughout the soil layer. In bare sandy land, as the entire soil layer is wet, the subsequent small precipitation can also replenish the deep soil layer moisture, as shown in Figure 3A. In the experimental area of Artamisia plot, heavy rainfall wets the entire soil layer, but for the root system soil water consumption, the subsequent small precipitation cannot significantly replenish the deep soil moisture, as shown in Figure 4D.



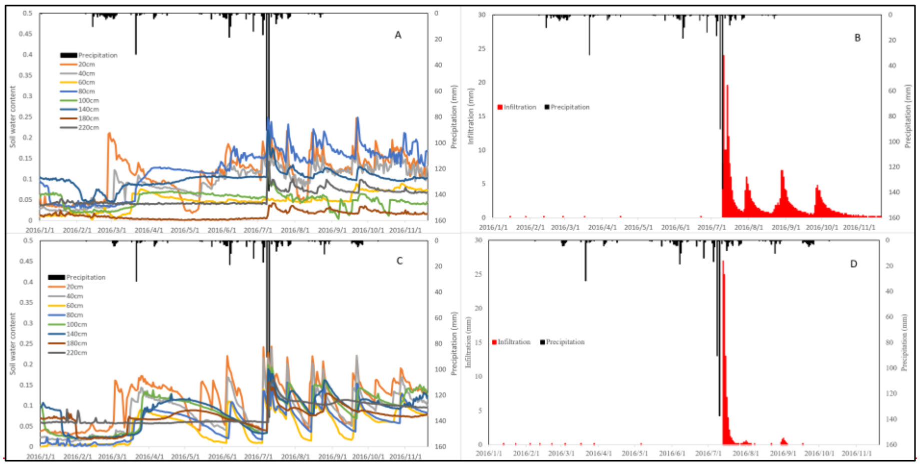


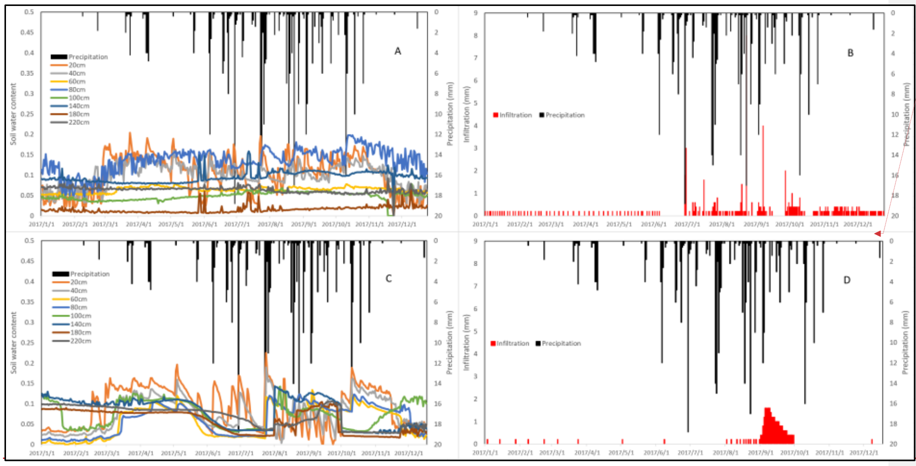
Figure 45. Effects of precipitation on soil moisture (A) and DSR (B) in bare sandy land plot; Effects of precipitation on soil moisture (C) and DSR (D) on ASK plot, 2016.

The relationship of precipitation on soil moisture and DSR in bare sandy land plot and ASK plot of 2017 is showed in Figure 56(A-D). There are 94 precipitation events throughout the year in 2017, with the maximum precipitation amount of 18.8 mm/d happened on June 29th, and the minimum precipitation amount of 0.2 mm/d happened 24 times throughout the year. On bare sandy land, there are 178 infiltration events throughout the year in 2017, with the maximum DSR amount of 8 mm/d, happened on August 23th, and the minimum DSR amount of 0.2 mm/d happened 128 times throughout the year. On the ASK plot, there are 52 infiltration

Formatted: Font: 9 pt

Formatted: Font: Not Italic

events throughout the year in 2017, with the maximum DSR amount of 1.6 mm/d, happened on September 5th, and the minimum DSR amount of 0.2 mm/d happened 21 times throughout the year. There were only 6 times of infiltration in bare sand plot from January to April in 2016, and 50 times in 2017, as shown in Figures 4 and 5. Since the surface is frozen at this time, there will be no surface infiltration. The source of infiltration in the first three months is essentially from the soil layer reservoir of 2016. One can speculate that the accumulation of water in the soil in the previous year can continue to infiltrate to the second year. This also makes it difficult to subdivide which precipitation process induced how much soil water content. In 2017, there was less precipitation than the previous year, so the DSR was reduced in both plots, especially the ASK plot. Only after the vegetation had dried up in September 9th did a large infiltration process occurred.



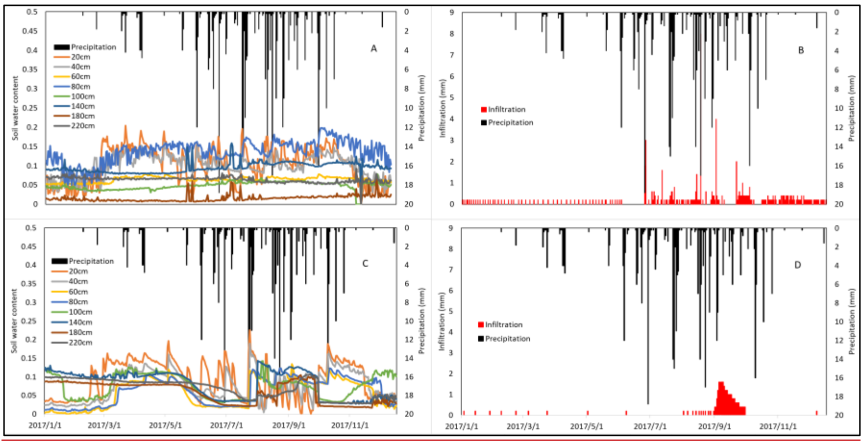


Figure ~~5~~ 6 Effects of precipitation on soil moisture (A) and DSR (B) in bare sandy land plot; Effects of rainfall on soil moisture (C) and DSR (D) on ASK plot, 2017.

The results show that in the Mu Us Sandy Land, whether there is vegetation coverage or not, DSR occurs in all seasons of the year and there is a significant difference in terms of DSR characteristics in the bare sand plot and the ASK plot. More specifically, the annual DSR of the bare sandy lands reaches 3.13 times of that of the ASK land. After the freeze-thaw period, the ASK root system begins to utilize the soil moisture, and soil moisture consequently decreases significantly.

Formatted: Justified, Indent: First line: 0.63 cm, Line spacing: Double, Don't keep with next

Formatted: Font: 12 pt

The relationship between precipitation and soil moisture content fluctuations and DSR in 2018 is shown in Figure 67(A-D). There are 71 precipitation events throughout the year in 2018, with the maximum precipitation amount of 30 mm/d happened on August 31th, and the minimum precipitation amount of 0.2 mm/d happened 15 times throughout the year. On bare sandy land, there are 122 infiltration events throughout the year in 2018, with the maximum DSR of 1.6 mm/d happened on June 4th, and the minimum DSR of 0.2 mm/d happened 74 times throughout the year. On ASK plot, there are 10 infiltration events throughout the year in 2016, with the maximum and the minimum DSR at the same amount of 0.2 mm/d happened 10 times throughout the year.

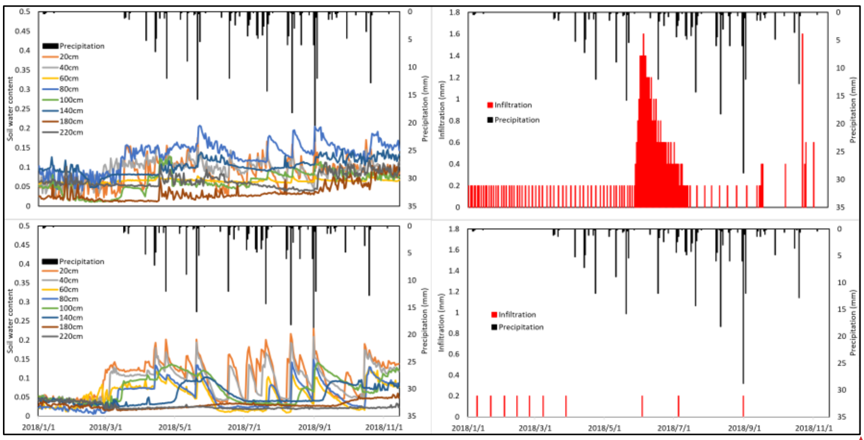


Figure 6 7 Effects of precipitation on soil moisture (A) and DSR (B) in bare sandy land plot; Effects of rainfall on soil moisture (C) and DSR (D) on ASK plot, 2018.

The results show that under the heavy precipitation event on August 31th, 2018, DSR in the bare sandy land is obviously visible. The precipitation replenishes deep soil layer and shallow groundwater. However, in the ASK plot, a large percentage of precipitation-induced infiltration is intercepted by vegetation coverage, meaning that the sand-fixing vegetation strongly affects the infiltration process and has a greater impact on groundwater recharge. At the same time, DSR can be found in both plots in all seasons throughout the year.

Formatted: Justified, Indent: First line: 0.63 cm, Line spacing: Double, Don't keep with next

Formatted: Font: 12 pt

Formatted: Normal, Justified, Indent: First line: 2 ch, Space Before: 1 line, After: 1 line, Line spacing:

3.5 Research on rain-feed ASK land water distribution

There are many methods of measure surface layer evapotranspiration, but all have poor precise, because there are many factors that affect surface layer evapotranspiration and one cannot consider all impact factors, these factors including vegetation coverage, environmental and temperature factors. This study treats shallow soil as a whole layer and measures the amount of surface rainfall recharge, soil water storage and DSR directly. Based on the directly measured DSR and precipitation, the soil moisture storage change can be calculated using equation (1). During the five-month intermittent frozen period, soil moisture sensors provide less reliable soil water content measurements as the soil moisture sensors are designed to detect liquid water instead of solid ice. Therefore, this research uses the unfrozen time period from April 1th to November 30th to investigate the water distribution. The average soil water contents in the first week of April and the first week of November are used as the initial and final values of annual soil water storage, to calculate the change of soil water storage annually. Based on measured precipitation, DSR and soil water storage, and the water balance equation (1), the evapotranspiration can be accurately calculated and the results are shown in Table 4.

In 2016, the soil moisture reserve in the 220 cm soil layer of bare sand increased by 47.15 mm, and the annual evaporation was 134.04 mm, while the soil water storage of Artamisia plot increased by 31.95 mm, and the evapotranspiration was 342.25 mm. In 2017, the soil water storage of bare sandy plot increased by 13.77 mm, and the annual evaporation was 232.03 mm, while the soil water storage of Artamisia plot was reduced by 83.7 mm, and the evapotranspiration was 365.9 mm. In 2018, the soil water storage of bare sandy plot increased by 72.14 mm, and the annual evaporation was 121.46 mm, while the soil water storage of Artamisia plot increased by 2 mm, and the evapotranspiration was 202.63 mm. One should be noted that the change in soil water storage only represents the distribution of soil moisture from April to November, rather than the net increase of the whole year, because the water in the soil will continue to infiltrate to deep soil layer when the surface soil layer is frozen. As shown in Figure 3, there is no significant precipitation from January to June 2017, but deep infiltration has been occurring. Comparing the data from 2016 to 2018 in Table 4~~5~~, it can be found that when there is sufficient precipitation, for example, in 2016, soil water storage increases and evapotranspiration increases as well. When the precipitation is low, the soil water storage decreases and the evapotranspiration decreases as well. The results show that after vegetation reconstruction in this area, the amount of DSR is significantly reduced, which may threaten the safety of groundwater recharge; The precipitation water resource is concentrated in the shallow soil layer, vegetation gets sufficient moisture, then evaporation increases, and the regional microclimate environment will be improved. Evapotranspiration of plants in drought years is significantly reduced, which shows that vegetation will adapt to the environment by increasing or decreasing water consumption according to the amount of precipitation.

Table 4. Annual water distribution of ASK land and bare sand field

Year	Field type	Precipitation (mm)	DSR (mm)	Change of the SWS (mm)	Evapotranspiration (mm)
2016	Bare sand plot	464.8	283.6	47.15	134.05
	ASK plot	464.8	90.6	31.95	342.25
2017	Bare sand plot	313.4	67.6	13.77	232.03
	ASK plot	313.4	31.2	-83.7	365.9
2018	Bare sand plot	245.2	51.6	72.14	121.46
	ASK plot	245.2	2	40.57	202.63

*Note: SWS stands for soil water storage.

3.6 Influence of vegetation coverage on infiltration rate

In many aspects one can find the influence of vegetation on infiltration, the interception of precipitation by the aboveground part of vegetation, the interception and absorption of surface soil layer moisture by vegetation, the absorption and utilization of soil water by vegetation roots, the root system occupying soil voids to reduce infiltration speed, and the conduction effect of the catheter formed by death root on the infiltration ability. In this study, we consider the above-ground and underground parts of vegetation as a whole system, and compare the bare sand plot and ASK plot on the infiltration speed. During the observation period, the Precipitation-DSR interaction occurred alternatively. In order to show the characteristics of the two types of infiltration, we selected a typical infiltration process, and the result is shown in Figure ~~7~~8. A precipitation of 90.2 mm/d was generated at 23:00 on July 7, 2016, and a DSR event was observed at 21:00 on July 9 on the bare sand plot. From the surface soil layer to 220 cm depth soil layer, the infiltrate process took 46 hours. The DSR of the ASK plot was observed at 8:00 on July 12, and the infiltrate process from the surface layer to the depth of 220 cm soil layer took 107 hours. The infiltration rate of ASK plot is 2.33 times of bare sandy land. One can see that vegetation cover significantly affects the infiltration rate. However, under natural conditions, multiple precipitation processes occur in a short period, so it is difficult to distinguish the DSR event caused by a certain precipitation of different land coverage types under sufficient precipitation.

The results show that the characteristics of precipitation-induced DSR in the sandy land plot and the ASK plot are different. The two precipitation events leave marks on the bare sandy plot, leading to two spikes of DSR. In contrast, such spikes do not appear in the ASK plot, because water is utilized by the root system mostly and only a very small portion of the precipitation-induced infiltration can reach as far as 220 cm to be detected by the lysimeter. ASK not only delays the infiltration rate but also reduces the total amount of DSR.

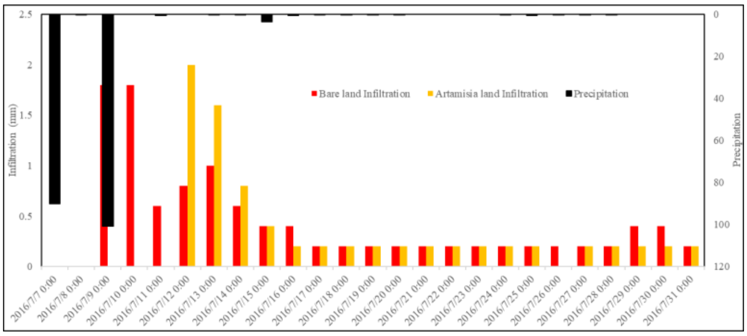


Figure ~~7~~8. DSR response to precipitation on bare sandy plot and ASK plot

4. Discussion

Monitoring and quantifying precipitation induced shallow groundwater recharge process is a long-lasting challenges in the hydrological communities, and it is especially difficult to do so in arid and semi-arid regions because of the spatiotemporally highly variable precipitation and complex soil moisture dynamics during the infiltration process (Newman et al., 2006). Studies of the interrelationship of precipitation and shallow groundwater is very important to local vegetation reconstruction, with or without anthropogenic mitigation (Ramier et al., 2009;Scibek et al., 2007). The difficulty of attempting to establish a relationship between precipitation and groundwater recharge is mainly reflected in the following aspects. Firstly, there are fewer instruments for direct long-term, large-scale measurements (Krishnaswamy et al., 2013). The commonly used methods such as double ring filter method, lysimeter, rainfall simulation method, water flux method and stable isotope based tracking methods all have certain specific restrictions (Sprenger et al., 2015;Groh et al., 2018). For instance, the heterogeneous nature of soil and point observations made with most above mentioned methods will make it difficult to conduct a basin scale analysis (Mousavi and Shourian, 2010). Secondly, ecological elements (such as ASK root systems in this study) are always changing, thus any monitoring methods that cannot continuously accommodate the ecological elements will miss a significant piece of the machinery of understanding the precipitation-recharge relationship.

Our research here is an attempt to utilize a low-cost, field-based lysimeter method to monitor DSR for four years in Mu Us sandy land, a task that measure DSR without disturbing the horizontal flow of soil moisture has never been reported before.

The improvement of soil texture takes hundreds of years. It also takes a long time to improve soil texture with the participation of vegetation roots. In the Mu Us Sandy Land, due to the participation of the sand-fixing vegetation, a large number of dust particles are fixed by the sand-fixing vegetation. When rainfall happens, water infiltrates into the deep soil with these dust. Over the forty years, the texture of the soil in this plot has undergone significant changes. From this one can infer that the rate of soil improvement in this area far exceeds our expectations.

In semi-arid areas, Mu Us sandy land as an example, the main limiting factor for trees is available water resources (Gao et al., 2014;Skarpe, 1991). Therefore, the key to understand the vegetation ecosystem in semi-arid areas is to study the supply of water resources (Cheng et al., 2018a;Cheng et al., 2017a). The ASK has been in existence in the study area for more than 40 years, so the purpose of this study is to find out whether there is sufficient water resource available in the region to support vegetation ecosystem, through the measurement of DSR. The “sustainable” growth of plants in this study means that water resource from precipitation can meet the growth needs of ASK, and can still have an excess amount of water to replenish deep soil layer. In this study, the soil moisture distribution has been studied by using the newly designed lysimeter to measure whether the soil layer below the root layer could produce DSR or not.

In the dry years, the differences in soil water storage and DSR between the two plots are significant, taking 2018 as an example. At the beginning of the experiment, the soil moisture storage in the ASK plot is 126.16 mm, and the soil moisture storage of bare sandy land is

147.22 mm. At the end of the experiment, the soil moisture storage in the ASK plot is 166.72 mm, which is 40.56 mm less than that at the beginning of the experiment. The soil moisture storage of the bare sandy plot at the end of the experiment is 219.37 mm, which is 72.15 mm more than its counterpart at the beginning of the experiment. There is no significant difference in soil water storage, but the DSR difference is obvious. The DSR of bare sand is 51.6 mm, and that of ASK plot is only 2 mm. Although the DSR is significantly reduced, even in the dry years, there is still a small amount of DSR, indicating that the selection of ASK as sand-fixing vegetation in this area is a suitable plant species. Another interesting point to note is that ASK is capable of adjusting their own growth conditions based on the available moisture recharge, and a larger moisture recharge will result in a faster growth rate of such plants. When the rainfall is insufficient, the evapotranspiration of ASK is reduced from 342.25 mm in 2016 to 202.63 mm in 2018.

As surface soil is frozen and ASK enters dormancy during winter in the research site, snow can only accumulate on the surface and cannot recharge soil moisture. However, moisture in deep soil continues to infiltrate downwards because of the driving force of gravity. This is particularly true in bare sandy land as a large amount of soil moisture has been accumulated at the start of the frozen period. A portion of those accumulated soil moisture will slowly infiltrate downwards and recharge groundwater reservoir. Because the amount of snowfall in winter is difficult to calculate, the amount of frozen water accumulated in winter cannot be obtained. How to accurately obtain the details of winter infiltration requires further research. Traditional lysimeter has~~ve~~ impervious containers for loading plants. The air in the container will cause increased DSR when it expands and contracts. Some researchers hypothesized ~~–~~that ~~it~~the increased DSR comes from condensed water generated by soil water vapor. The newly designed lysimeter of this study is expected to be less influenced by the condens~~at~~ed water ~~for~~because there is no container for loading plants. But ~~it~~one should also be aware that condensed water may still exist in sandy soil layer and its influence on the soil dynamics including the measurement of DSR, soil moisture variation, and ET is still poorly quantified. This is an issue that deserves further investigation. Another point to note is that although vegetation in arid areas grows slowly, the amount of water that becomes plant tissue during the growth is relatively small, and most water is consumed by evapotranspiration. The tissue water consumed by vegetation is not calculated separately in this research but is counted in evapotranspiration.

5. Conclusions

This research uses a newly designed lysimeter to monitor shallow soil layer infiltration, and results show that in order to absorb more precipitation moisture, ASK develops a horizontal root system and retains more water in the shallow soil layer. ASK has shown to be effective in fixing the mobile sand and increasing the proportion of fine particles in the sandy land. ASK changes its own evapotranspiration mount to adapt to the annual precipitation changes. Under the existing precipitation conditions, the ASK community can develop healthily, as a small amount of precipitation can recharge the groundwater, even in dry year. This indicates that precipitation in the area is sufficient to meet the needs of vegetation water consumption. However, with the unforeseeable global warming and abnormal precipitation events, semi-arid region may become drier and the ASK community may be seriously affected. Therefore, continuously monitoring the key controlling factors associated with the ecological system in the semi-arid region is needed.

The following conclusions can be drawn from this research:

1) In Mu Us sandy land, the ASK root system develops horizontally to absorb more precipitation-induced infiltration. The root system reaches 120 cm depth and mainly concentrates within the upper 40 cm deep soil layer.

2) After 40 years of vegetation reconstruction, the soil particle size distribution has been significantly changed, soil texture improvement in semi-arid sandy land far exceeds expectations. Specifically, the sandy soil mainly consisting of medium sand (50.53%) grows into a sandy soil mainly consisting of fine sand (60.53%). Vegetation is particularly important in semi-arid areas since it directly changes the composition of soil.

3) The yearly DSR in the ASK sand-fixing experimental plot is from 2 mm to 90.6 mm. In contrast, the yearly DSR in the bare sand plot is from 51.6 mm to 283.6 mm. This shows that the rainfed vegetation has reduced DSR substantially but there is still a small amount of recharge left to replenish the deep soil moisture, implying that the current ASK community is still hydrologically self-sustainable because it does not consume all the water moisture replenished by precipitation and the DSR has not been reduced to zero.

4) With the coverage of ASK at this stage, the sand-fixing forest in the Mu Us Sandy Land does not cause disconnection between atmospheric water and ground water. During the observation period, the infiltration of bare sandy land can reach 25.8 times of ASK land, and during a single precipitation process, the infiltration rate of ASK plot can reach 2.33 times of bare sandy land.

Acknowledgements

This research was supported by the Major Program of the National Natural Science Foundation of China, National Science and Technology Major Project and Ministry of Science and Technology of China (No. 2017ZX07101004, No. 2018YFC0507100, NO. 2019ZD003), the National Non-profit Institute Research Grant of Chinese Academy of Forestry (grant number CAFYBB2018ZA004) and the research grants from the Fundamental Research Funds for the

Central Universities (BLX201814). We gratefully acknowledge the Beijing Municipal Education Commission for their financial support through Innovative Transdisciplinary Program "Ecological Restoration Engineering". Thanks to the experimental site provided by Inner Mongolia Dengkou Desert Ecosystem National Observation Research Station, the Experimental Center of Desert Forestry, Chinese Academy Forestry. The authors thank two anonymous reviewers for their constructive comments which help improve the quality of the manuscript.

Competing Interests

Formatted: Space Before: 1 line, After: 1 line

The authors declare that they have no conflict of interest

Authors' contributions: Author contributions: C.YB., Y.WB., and Z.HB., conceived the idea; C.YB., J.QO., and W.YQ., conducted the analyses; C.YB., S.MC., and Y.WB., provided the data; all authors contributed to the writing and revisions.

References

Formatted: Indent: Left: 0 cm, Hanging: 2 ch, First line: -2 ch, Line spacing: Double

Field Code Changed

[1] Bestelmeyer, B. T., Okin, G. S., Duniway, M. C., Archer, S. R., Sayre, N. F., Williamson, J. C., and Herrick, J. E.: Desertification, land use, and the transformation of global drylands, Frontiers in Ecology and the Environment, 13, 28-36, 2015.

[2] Billesbach, D. J. A., and Meteorology, F.: Estimating uncertainties in individual eddy covariance flux measurements: A comparison of methods and a proposed new method, 151, 394-405, 2011.

[3] Burba, G., and Anderson, D.: A brief practical guide to eddy covariance flux measurements: principles and workflow examples for scientific and industrial applications, Li-Cor Biosciences, 2010.

[4] Chen, C., Park, T., Wang, X., Piao, S., Xu, B., Chaturvedi, R. K., Fuchs, R., Brovkin, V., Ciais, P., and Fensholt, R.: China and India lead in greening of the world through land-use management, Nature Sustainability, 2, 122, 2019.

[5] Cheng, Y., Zhan, H., Yang, W., Dang, H., and Li, W.: Is annual recharge coefficient a valid concept in arid and semi-arid regions, Hydrol. Earth Syst. Sci, 21, 5031-5042, 2017a.

[6] Cheng, Y., Zhan, H., Yang, W., Dang, H., Li, W. J. H., and Sciences, E. S.: Is annual recharge coefficient a valid concept in arid and semi-arid regions?, 21, 5031, 2017b.

[7] Cheng, Y., Li, Y., Zhan, H., Liang, H., Yang, W., Zhao, Y., and Li, T.: New comparative experiments of different soil types for farmland water conservation in arid regions, Water, 10, 298, 2018a.

[8] Cheng, Y., Li, Y., Zhan, H., Liang, H., Yang, W., Zhao, Y., and Li, T. J. W.: New comparative experiments of different soil types for farmland water conservation in arid regions, 10, 298, 2018b.

[9] Cheng, Y., Zhan, H., Yang, W., Guo, F., Jiang, Q., and Wang, Y.: On change of soil moisture distribution with vegetation reconstruction in Mu Us sandy land of China, with new designed Lysimeter, 2020.

[10] D'Odorico, P., Bhattachan, A., Davis, K. F., Ravi, S., and Runyan, C. W.: Global desertification: drivers and feedbacks, Advances in Water Resources, 51, 326-344, 2013.

[11] Dregne, H. E., and Chou, N.-T.: Global desertification dimensions and costs, Degradation and restoration of arid lands, 73-92, 1992.

[12] Duan, H., Yan, C., Tsunekawa, A., Song, X., Li, S., and Xie, J.: Assessing vegetation dynamics in the Three-North Shelter Forest region of China using AVHRR NDVI data, Environmental Earth Sciences, 64, 1011-1020, 2011.

[13] Fan, Y., Miguez-Macho, G., Jobbágy, E. G., Jackson, R. B., and Otero-Casal, C. J. P. o. t. N. A. o. S.: Hydrologic regulation of plant rooting depth, 114, 10572-10577, 2017.

[14] Fearnehough, W., Fullen, M., Mitchell, D., Trueman, I., and Zhang, J. J. G.: Aeolian deposition and its effect on soil and vegetation changes on stabilised desert dunes in northern China, 23, 171-182, 1998.

[15] Gao, Y., Zhu, X., Yu, G., He, N., Wang, Q., and Tian, J.: Water use efficiency threshold for terrestrial ecosystem carbon sequestration in China under afforestation, Agricultural and Forest Meteorology, 195, 32-37, 2014.

[16] Groh, J., Stumpp, C., Lücke, A., Pütz, T., Vanderborght, J., and Vereecken, H.: Inverse estimation of soil hydraulic and transport parameters of layered soils from water stable isotope and lysimeter data, Vadose Zone Journal, 17, 2018.

[17] Hanjie, W., and Hao, Z.: A simulation study on the eco-environmental effects of 3N Shelterbelt in North China, Global and Planetary Change, 37, 231-246, https://doi.org/10.1016/S0921-8181(02)00208-4, 2003.

[18] Krishnaswamy, J., Bonell, M., Venkatesh, B., Purandara, B. K., Rakesh, K., Lele, S., Kiran, M., Reddy, V., and Badiger, S.: The groundwater recharge response and hydrologic services of tropical humid forest ecosystems to use and reforestation: Support for the "infiltration-evapotranspiration trade-off hypothesis", Journal of Hydrology, 498, 191-209, 2013.

[19] Li, H.-r., Liu, Q.-b., Wang, W.-y., Yang, L.-s., Li, Y.-h., Feng, F.-j., Zhao, X.-y., Hou, K., and Wang, G. J. J. o. H. M.: Fluoride in drinking water, brick tea infusion and human urine in two counties in Inner Mongolia, China, 167, 892-895, 2009.

[20] Li, X. R., Ma, F. Y., Xiao, H. L., Wang, X. P., and Kim, K. C.: Long-term effects of revegetation on soil water content of sand dunes in arid region of Northern China,

Field Code Changed

Journal of Arid Environments, 57, 1-16, https://doi.org/10.1016/S0140-1963(03)00089-2, 2004.

[21] Liu, J., and Diamond, J.: China's environment in a globalizing world, Nature, 435, 1179, 10.1038/4351179a, 2005.

[22] Liu, X., He, Y., Zhao, X., Zhang, T., Zhang, L., Ma, Y., Yao, S., Wang, S., and Wei, S.: Characteristics of deep drainage and soil water in the mobile sandy lands of Inner Mongolia, northern China, Journal of Arid Land, 7, 238-250, 10.1007/s40333-014-0095-4, 2015.

[23] Maes, W. H., Gentine, P., Verhoest, N. E., Miralles, D. G. J. H., and Sciences, E. S.: Potential evaporation at eddy-covariance sites across the globe, 23, 925-948, 2019.

[24] Mousavi, S. J., and Shourian, M.: Adaptive sequentially space-filling metamodeling applied in optimal water quantity allocation at basin scale, Water Resources Research, 46, 2010.

[25] Newman, B. D., Vivoni, E. R., and Groffman, A. R.: Surface water–groundwater interactions in semiarid drainages of the American southwest, Hydrological Processes: An International Journal, 20, 3371-3394, 2006.

[26] Pei, S., Fu, H., Wan, C. J. A., Ecosystems, and Environment: Changes in soil properties and vegetation following exclosure and grazing in degraded Alxa desert steppe of Inner Mongolia, China, 124, 33-39, 2008.

[27] Ramier, D., Boulain, N., Cappelaere, B., Timouk, F., Rabanit, M., Lloyd, C. R., Boubkraoui, S., Métayer, F., Descroix, L., and Wawrzyniak, V.: Towards an understanding of coupled physical and biological processes in the cultivated Sahel–1. Energy and water, Journal of Hydrology, 375, 204-216, 2009.

[28] Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B., Mortimore, M., Batterbury, S. P., Downing, T. E., Dowlatabadi, H., Fernández, R. J., and Herrick, J. E.: Global

Field Code Changed

desertification: building a science for dryland development, science, 316, 847-851, 2007a.

[29] Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B. L., Mortimore, M., Batterbury, S. P. J., Downing, T. E., Dowlatabadi, H., Fernández, R. J., Herrick, J. E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F. T., Ayarza, M., and Walker, B.: Global Desertification: Building a Science for Dryland Development, Science, 316, 847-851, 10.1126/science.1131634, 2007b.

[30] Scibek, J., Allen, D. M., Cannon, A. J., and Whitfield, P. H.: Groundwater–surface water interaction under scenarios of climate change using a high-resolution transient groundwater model, Journal of Hydrology, 333, 165-181, 2007.

[31] Skarpe, C.: Spatial patterns and dynamics of woody vegetation in an arid savanna, Journal of Vegetation Science, 2, 565-572, 1991.

[32] Sprenger, M., Volkmann, T. H., Blume, T., and Weiler, M.: Estimating flow and transport parameters in the unsaturated zone with pore water stable isotopes, Hydrology and Earth System Sciences, 2015.

[33] Su, Y. Z., and lin Zhao, H.: Soil properties and plant species in an age sequence of Caragana microphylla plantations in the Horqin Sandy Land, north China, Ecological Engineering, 20, 223-235, 2003.

[34] Tao, W.: Aeolian desertification and its control in Northern China, International Soil and Water Conservation Research, 2, 34-41, https://doi.org/10.1016/S2095-6339(15)30056-3, 2014.

[35] Wang, S., Cornelis van Kooten, G., and Wilson, B.: Mosaic of reform: forest policy in post-1978 China, Forest Policy and Economics, 6, 71-83, https://doi.org/10.1016/S1389-9341(02)00078-3, 2004.

Field Code Changed

Field Code Changed

[36] Wang, T., Sun, J.-g., Han, H., and Yan, C.-z.: The relative role of climate change and human activities in the desertification process in Yulin region of northwest China, Environmental Monitoring and Assessment, 184, 7165-7173, 10.1007/s10661-011-2488-6, 2012.

[37] Wang, X., Zhang, C., Hasi, E., and Dong, Z.: Has the Three Norths Forest Shelterbelt Program solved the desertification and dust storm problems in arid and semiarid China?, Journal of Arid Environments, 74, 13-22, 2010a.

[38] Wang, X. M., Zhang, C. X., Hasi, E., and Dong, Z. B.: Has the Three Norths Forest Shelterbelt Program solved the desertification and dust storm problems in arid and semiarid China?, Journal of Arid Environments, 74, 13-22, https://doi.org/10.1016/j.jaridenv.2009.08.001, 2010b.

[39] Wang, Y., Zhao, H.-L., and Zhao, X.-Y.: Effects of land use intensity on the restoration capacity of sandy land vegetation and soil moisture in fenced sandy land in desert area, Contemporary Problems of Ecology, 6, 128-136, 2013.

[40] Yan, Y., Xin, X., Xu, X., Wang, X., Yang, G., Yan, R., Chen, B. J. P., and soil: Quantitative effects of wind erosion on the soil texture and soil nutrients under different vegetation coverage in a semiarid steppe of northern China, 369, 585-598, 2013.

[41] Yu, C., Muñoz-Carpena, R., Gao, B., and Perez-Ovilla, O. J. J. o. h.: Effects of ionic strength, particle size, flow rate, and vegetation type on colloid transport through a dense vegetation saturated soil system: Experiments and modeling, 499, 316-323, 2013.

[42] Zha, Y., and Gao, J.: Characteristics of desertification and its rehabilitation in China, Journal of Arid Environments, 37, 419-432, https://doi.org/10.1006/jare.1997.0290, 1997.

[43] Zhang, G.-H., Liu, G.-B., Wang, G.-L., Wang, Y.-X. J. J. o. S., and Conservation, W.: Effects of vegetation cover and rainfall intensity on sediment-associated nitrogen and

phosphorus losses and particle size composition on the Loess Plateau, 66, 192-200, 2011.

Formatted: Line spacing: Double