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Research Article

INTERNATIONAL JOURNAL OF PLANT, ANIMAL AND ENVIRONMENTAL SCIENCES

ISSN: 2231-4490

The Theory of Sandy Land Soil Hydrology and Mode of Low Coverage Afforestation in Northwest China

Mingyuan Wang*

Abstract

Most of the sandy land areas in northwest China belong to semi-arid area and the average annual rainfall is about 250-500 mm. Sandy land has the potential to reverse itself when man-made pressure is removed. The specific permeability structure of sandy soil showed heterogeneous anisotropy in the horizontal direction (x or y) of the soil surface (0-10cm) and showed interlayer homogeneity and isotropy in the vertical direction (z) of the underlying of soil surface, which formed rainfall infiltration process of the special combination of both channel flow and capillary flow percolation systems in sandy soil. It is reflected in the combination structure of "source" and "reservoir" in the soil water profile due to lateral gravity water recharge. There is no hydraulic relation between large area exposed sandy land and groundwater, and the model $AET = a\left(\beta \ln\left(1-\frac{\theta_i}{\theta_s}\right)\right)^{2b}$ of shrub community consuming soil water reflects the relationship between soil water deficit and free gravity water recharge in sandy land formed by precipitation. On the one hand, sandy land afforestation preserves a part of bare sandy land intermittently to gather surface and subsurface soil runoff (or called collecting internal drainage from source) and adopting sandy land afforestation methods and techniques with low coverage and patch vegetation configuration. On the other hand, shrub plants in sandy land have a higher root-shoot ratio. According to the balance between soil water storage (collection) and vegetation water consumption, plantation vegetation coverage in sandy land can be determined by the square of root-shoot ratio $C_p = 1 - e^{-\rho\left(\frac{RM}{GM}\right)^2}$. This formula indicates that the deep roots and horizontal ductility of plants in sandy land expand the soil water space available to vegetation under drought conditions so that the water consumption of transpiration is relatively supplemented. These two aspects are the key to the success of large-scale desertification control and afforestation.

Keywords: Northwest China; Sandy land; Soil hydrology; Afforestation

Introduction

There are two figures for desertification area in northwest China: 2.18 million km^2 and 600,000 km^2. The first data covers deserts, gobi and desert formed in geological history. The scope of the second data only refers to the desertification land caused by human causes and with the conditions to control it, namely in semi-humid, semi-arid areas, due to the effect of the natural and human factors and interference, to form similar to desert landscape types, called desertification land or sandy land [1]. The distribution of sandy land in China is bounded by Helan Mountain and has obvious regional characteristics. The area west of Helan Mountain, mainly including Xinjiang, Gansu, northwest

Affiliation:
Chinese Academy of Forestry, Haidian District, Xiangshan Rd, Beijing, China

***Corresponding author:**
Mingyuan Wang, Chinese Academy of Forestry, Haidian District, Xiangshan Rd, Beijing, China.

Citation: Mingyuan Wang. The Theory of Sandy Land Soil Hydrology and Mode of Low Coverage Afforestation in Northwest China. International Journal of Plant, Animal and Environmental Sciences. 14 (2024): 42-58.

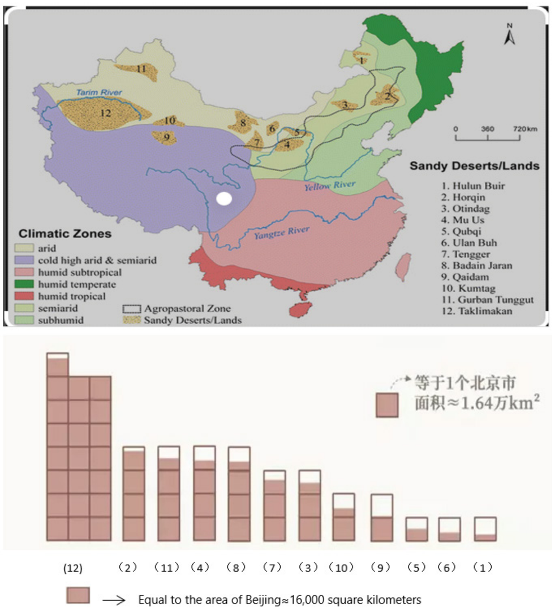
Received: June 28, 2024
Accepted: July 23, 2024
Published: July 30, 2024

Wang M., Int J Plant Anim Environ Sci 2024
DOI:10.26502/ijpaes.4490163

Tibet and western Inner Mongolia, has annual precipitation of less than 200 mm, which belongs to the "arid zone". Sandy land mainly distributed on the edge of the desert and near the oasis, and its distribution area accounting for 30.7% of the total area of the sandy land, its climate belongs to arid and it is difficult to control desertification, and poor self-reversal ability of desertified land. Therefore, it is necessary to pay attention to the rational use of water resources in oasis and areas with better natural conditions in the process of controlling desertification (Figure 1). The area east of Helan Mountain mainly includes the eastern part of Inner Mongolia Plateau, the western part of Loess Plateau and the central part of Qinghai-Tibet Plateau. It is the most widely distributed and harmful area of all kinds of desertification land, accounting for 69.3% of the total area of sandy land (Table 1). Most of the area belong to semi-arid area and the average annual rainfall is about 250-500 mm. Sandy land has the potential to reverse itself when man-made pressure is removed [2].

Table 1: Basic characteristics of sandy land in northwest China.

Name of the sandy land	Geomorphologic shape	Reference
Otindag Sandy Land	Most of the sandy land are fixed or semi-fixed dunes with ridges and chains shaped, and some of them is crescent shaped, spreading from northwest to southeast. The dunes are 10 to 30 meters high. There are a lot of marshy grasslands between the dunes and they are composed of light yellow powder sand.	[3]
Horqin Sandy Land	The most significant feature of the landform is that the sand layer has extensive coverage and the flat land between the hills is open, forming the topographic combination of dune and wetland landscape. The local people call it Tuo Dian. Sand dunes are mostly in the shape of gonggang in the direction of northwest and southeast, and there are sand and loess deposits in the laha River basin of the upper reaches of Xiliao River.	[4, 5]
The Mu Us sandy land	The Mu us Sand area is mainly located in the caulbron of lacustrine alluvial plain between Ordos plateau and Loess Plateau. All quaternary sediments are obviously sandy, and the loose sand layer is transported by wind to form easily moving quicksand.	[2]
Hulun Buir Sandy Land	The Hulun Buir Sandy land is located in the transition zone between forest and grassland with the superior geographical environment. The sand land is dominated by fixed and semi-fixed dunes, which provides vast land and rich biological resources for the comprehensive management of agriculture, animal husbandry and forestry production.	[6]
Sandy land and oases on the edge of deserts	The agricultural pastures in Xinjiang Reclamation area are banded in the southern edge of Gurbantunggut Desert, oasis on both sides of the river.	[7]



1) Hulunbuir Sandy Land 2) Horqin Sandy Land 3) The otindag sandy land 4) The Mu Us Sandy Land 5) The Kubuqi Desert 6）Ulan Buhe Desert 7) The Tengger Desert 8) The Badain Jaran Desert 9) Qaidam Basin Desert 10) The Kumtag Desert 11) Gurbantunggut Desert 12) The Taklimakan Desert

Figure 1: Distribution of desert and sandy land in Northwest China.

Data source: Status of Desertification in China, State Forestry Administration, 2015.

Citation: Mingyuan Wang. The Theory of Sandy Land Soil Hydrology and Mode of Low Coverage Afforestation in Northwest China. International Journal of Plant, Animal and Environmental Sciences.14 (2024): 42-58.

fortune Journals
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DOI:10.26502/ijpaes.4490163

Sand Fixation and Afforestation in Mobile Dunes

The surface morphology of mobile dunes is mostly composed of dunes and interdune lowlands (sand bay). Dunes are extremely arid, with high mobility and low water holding capacity. Direct plantation is easy to be eroded by wind and difficult to achieve results. Due to the low topography, sand accumulation environment and good moisture conditions, plants can survive in the interdune lowlands without artificial sand barriers. Afforestation and sand fixation should be carried out first in interdune lowlands and then in the dunes. Of course, it is feasible to carry out both technologies at the same time. For a mobile dune, afforestation of both the front and back interdune lowlands constitutes the sand fixation afforestation technology of "front blocking and back pulling".

Forest Belt Serving for Windbreak and Sand Resistance

The periphery of oasis and the zone adjacent to desert, gobi and wind-eroded land are the most important areas causing mobile dune and wind-eroded sand to the damage of oasis. Building large wind-resistant sand-forest belt in these areas have significant effects on preventing the invasion of mobile dune to oasis and weakening the occurrence of sandstorm in sand area. The windproof sand forest belt should be interwoven with patch forest, block forest and belt forest, so it is not necessary to force uniformity. Afforestation is mainly in the interdune land, wind-eroded land and gentle sandy land. Afforestation around the oasis first, and gradually expand and widen outwards. The dunes are separated and surrounded by clumps of interdune forests. With the dune moving forward, the dune top is flattened by the wind, and afforestation should be carried out at the retreating sand bank to expand the area of interdune forest and form a denser windproof and sand-blocking belt.

Analysis on the Basic Principle of Rainfall -Infiltration Process in Sandy Land

The soil in sandy land is mainly composed of fine sand and medium sand. Such particle size composition determines that there are less capillary pores and more large pores in sandy land. The dry sand layer formed by surface evaporation after rainfall can effectively reduce the evaporation loss in the soil layer below. When the sandy soil is in unsaturated state, it is generally divided into dry sand layer, wet sand layer and free water layer from top to bottom. During the period of rainfall, the bound water and film water of dry sand layer are rapidly replenished. The bound water and film water of wet sand layer below are saturated, deep sandy soil with particle size distribution of non-uniform coefficient between 1.2 and 1.5, pore size close to consistent, fast penetration and weak soil water-holding capacity. The diffusion of water movement controlled by the capillary force compared to that under gravity is negligible. Water infiltration is controlled by gravity and resistance caused by the flow, and the better drainage performance. There is an obvious wet front when rainfall infiltration. The depth of the wet front of the soil infiltrated by rainfall can be continuously moved down. Although the soil water flow speed is faster, the seepage is laminar flow, seepage Reynolds number $Re=Vd/\nu < 1$, in the formula, V represents the flow velocity, ν is the viscosity of liquid and d is the average particle size of the soil. The infiltration rate (or velocity V) and water potential gradient ψ show a linear relationship, and Darcy's law is valid, namely:

$$V=K_L\Psi \quad (1)$$

According to the velocity formula of laminar flow in a circular tube:

$$V=\gamma\Psi d^2/32\mu$$

Now, the average diameter of sandy soil pore d is used to replace the diameter of the circular tube:

$$K_L=C\gamma d^2/\mu$$

Where K_L is hydraulic conductivity (infiltration rate), γ is specific gravity of fluid, μ is dynamic viscosity of fluid, and C is constant. In the formula, γ and μ are only related to fluid, and the kinematic viscosity decreases and K_L increases with the increase of temperature. Cd^2 is only related to soil media in sandy land. For real soil, parameter C must cover the influence of other media characteristics unrelated to average particle size on fluid, such as particle size distribution, particle sphericity and roundness, and density of their filling. If defined:

There are:

$$K_L = k\gamma/\mu \quad (2)$$

If K_L is called hydraulic conductivity, the parameter *K* is called "specific permeability" or "intrinsic permeability". Specific permeability is the decisive factor of soil water conductivity and water holding capacity in sandy land. It has the following two meanings: (1) from the perspective of the infiltration path of soil water, it is mainly represented by the distribution of number (porosity) and size (d) through the pores and gaps existing in the soil. According to pore size, it can be divided into soil macropore, > 100μm, is the pore that can provide preferential water flow path, ventilation and drainage. Medium pore, 100-30μm, is characted as water conductivity high and water movement fast. Small pores, 30-3μm, is characted as water holding capacity and capillary water diffusion movement. Water enters the soil from macropores and mesopores with a positive pressure head, also known as "channel flow". The seepage flow in sandy land is uniform and consistent in all directions. The excavation of soil animals and the penetration of plant roots

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DOI:10.26502/ijpaes.4490163

make the infiltration path of "channel flow" warped in sandy land, so the hydraulic gradient is uncertain. The change of "channel flow" through soil profile of sandy land determines the size of water infiltration from the surface. Water infiltration through capillary action diffuses horizontally and vertically into smaller pores in the soil. As capillary flow increases with hydraulic gradient (suction/infiltration process), the film water thickness decreases. Infiltration is actually a combination of two seepage systems: channel flow and capillary flow. (2) Pore structure directly affects the path and mode of water migration in sandy soil surface and soil body and determining the hydraulic properties of soil such as water holding capacity, permeability and conductivity. Quantitative index parameters that can evaluate pore structure characteristics include pore equivalent diameter, pore number, porosity, pore connectivity and hydraulic radius. In a rainfall process, from the perspective of equivalent pore size, the number of small pore size increases, the number of large pore size decreases, and the pore area ratio decreases. The changes of soil pores in the topsoil layer are most obvious due to the direct impact of raindrops. From the perspective of soil connectivity, the topsoil layer is more affected, and the average Euler number increased (Euler number = (number of pores) - (number of fragments -1)). For the relationship of soil profile depth and the vertical spatial variability of porosity, generally, porosity decreases with the increase of sampling depth, that is, porosity can be used as an index to reflect the profile depth. In a rainfall process, porosity and hydraulic radius continue to decrease, while Euler number increases, indicating that the connectivity and conductivity of pores decrease with the duration of rainfall, and less conductive to water and solutes. In conclusion, soil hydraulic conductivity K_L varies with the specific permeability *K* structure in the whole soil profile space. At the same point of specific permeability structure, hydraulic conductivity will also change with different measurement directions (x,y,z). The former property is called "heterogeneity" and the latter "anisotropy". The characteristic of sandy soil is that the specific permeability structure is anisotropic in the x or y direction of soil surface (0-10cm). The soil profile below the surface layer shows interlayer homogeneity and isotropy (see Figure 2).

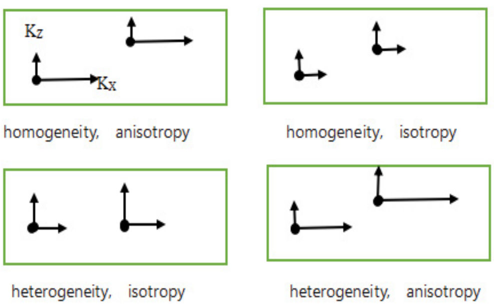
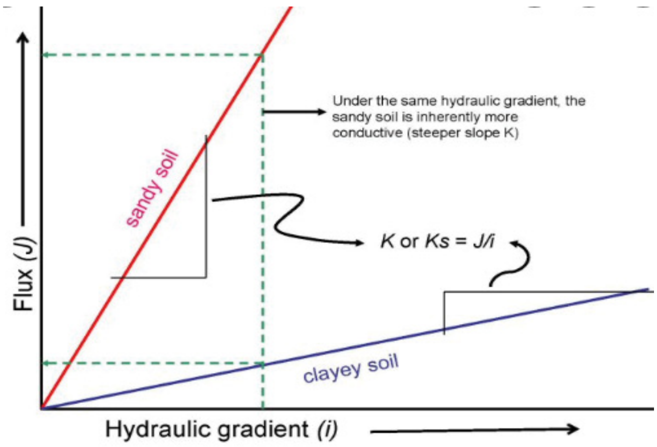


Figure 2: Four combinations of homogeneity, heterogeneity, isotropy and anisotropy.

The most significant factors affecting the process from rainfall to infiltration in bare sandy land are rainfall, rainfall process and rain type, soil texture in sandy land, homogenization degree of soil profile in x, y and z directions, soil water content (soil water potential) and distribution of soil surface crust layer. Soil moisture movement in different depth profile along the x, y, z three directions is a complicated process. It involves the dynamic flow process of water, air and water vapor in soil saturated and unsaturated zones driven by the physical mechanisms such as hydraulic gradient (see Figure 3), temperature gradient, concentration gradient and seepage gradient. It is the process by which the soil aeration zone redistributes rainwater. In each direction of the underlying surface (x, y, z), different soil moisture components are generated (some rainwater replenishes soil moisture, while others generate free water that is not absorbed by the soil, such as surface runoff, soil flow or subsurface flow).



Source: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_053573

Figure 3: A diagram showing the relationship between flux and hydraulic gradient. Hydraulic conductivity (K) is the slope that defines the relationship. The dotted lines show that at equal hydraulic gradients, soils with higher conductivity have higher flux.

Concepts such as Darcy's law, hydraulic head (water potential) and hydraulic conductivity are based on saturated media (all soil voids are filled with water). It is difficult to carry out the experiment of unsaturated water flow law (experiment of equal soil water content and equal soil water potential gradient). Theoretically, according to the regularity of vertical one-dimensional infiltration rate in unsaturated soil, it is lack of the general effective formula of soil water characteristic function such as water conductivity ($K_L(\theta)$, θ is soil water content) and diffusivity ($D(\theta)$). However, the constant value or linear function hypothesis, such as water retention curve of power function model and unsaturated hydraulic conductivity curve (see Figure 4), are adopted to simulate soil infiltration of quantitative rainfall. In reality, the obvious difference between unsaturated flow and

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saturated flow is that the water flux (hydraulic conductivity) on different sections of the whole unsaturated zone is not equal. The observation test of rainfall in sandy land proves that there are two conditions in the process of infiltration: (1) When the wet front extends downward through the surface soil but does not reach the groundwater level completely,the boundary is in unsaturated infiltration state. When the wet front reaches the groundwater table, the soil is saturated, and the surface infiltration rate is equal to saturated permeability (K_L). (2) When the rainfall intensity is less than the saturated permeability coefficient of soil, or the depth of the wet front formed by rainfall infiltration fails to reach the groundwater level, the final infiltration can only be in the state of unsaturated infiltration which the gradient of wetting front is larger compared with the rainfall infiltration front which is larger than saturated permeability. In arid and semi-arid areas, there is strong evaporation and little rainfall in sandy land. In case of precipitation, the water deficit caused by soil drought needs to be replenished first. Except for deep seepage caused by channel flow in dune lowland and sandy land, there is seldom deep seepage from sandy land infiltration to free water table.

In conclusion, infiltration intensity varies with rain type (rain intensity varies with time) and physical characteristics of infiltration interface during a rainfall process. The ability to drain through the soil:

$$I_1 = \frac{\theta_s - \theta_f}{\theta_s} \quad (3)$$

reflecting the spatial response of large pore flow or channel flow at the infiltration interface, where, I_1 is the internal drainage capacity within the depth of soil layer L_i, reflecting the response of the soil gravity water environment of the large pore channel flow at the infiltration interface, θ_s is the saturated water content of soil layer L_i, θ_f is the field water capacity of soil layer L_i and L_i reflecting the environmental response of drainage in soil layer L_i. The ability to diffuse through soil moisture:

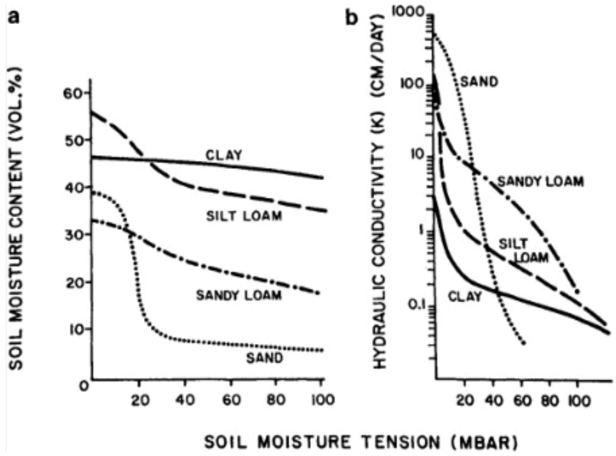

Figure 4: Diagram of comparison of hydraulic conductivity and soil water tension curves of different soil types [1].

$$I_2 = \frac{\theta_f - \theta_i}{\theta_s} \quad (4)$$

reflecting the spatial response of small pore flow (capillary pore flow), where, I_2 is the soil water diffusion capacity through the soil layer L_i, when θ_i is the water content of the soil layer L_i, θ_f is the field water holding capacity of the soil layer L_i, $\theta_f > \theta_i$ reflecting the response of soil capillary pore flow environment. The time response of piston infiltration the infiltration interface can be reflected by the layer thickness L_i evolving from the infiltration front (Table 2). The sum I_L of the gravity drainage capacity I_1 and diffusion capacity I_2 in the soil is called the ability to convert rainfall of the soil layer L_i, $I_L = I_1 + I_2$, which is the index of the soil layer's ability to hold water and recharge groundwater, namely, the hydraulic conductivity K_L of the soil layer L_i, and for L_i and I_L, there is the following exponential function relationship:

$L_i = \alpha (I_L)^\beta$, where, α(>0) and β(>0) are coefficient and exponent respectively.

To take logarithm and differentiate to introduce rainfall factor P (absorbed rainfall per unit infiltration depth): $d\ln L_i = (d\ln\alpha (I_L)^\beta)\left(\frac{P}{L_i}\right)$, integral to : $\frac{L_i}{P} = \ln\alpha (I_L)^\beta + C$, when $I_1 \to 0, I_2 \to 1, I_L = 1, L_i \to 0, C = -\ln\alpha$, Arrange as follows:

$$P = \frac{L_i}{\beta \ln I_L} \text{ or } P = \frac{L_i}{\beta \ln\left(1 - \frac{\theta_i}{\theta_s}\right)} \quad (5)$$

To take logarithm and differentiate to introduce rainfall factor P (infiltration depth of per unit rainfall): $d\ln L_i = (d\ln\alpha (I_L)^\beta)\left(\frac{L_i}{P}\right)$, Integral to : $-\frac{P}{L_i} = \ln\alpha (I_L)^\beta + C$, when $I_1 \to 1, I_2 \to 0, I_L = 1, L_i \to \infty$, $C = -\ln\alpha$, Arrange as follows :

$$L_i = -\frac{P}{\beta \ln I_L} \text{ or } L_i = -\frac{P}{\beta \ln\left(1 - \frac{\theta_i}{\theta_s}\right)} \quad (6)$$

In a general sense, the soil in sandy land is in the process of holding water and transforming rainfall into groundwater, I_L drainage capacity in the direction of the (x, y or z) depends on soil hydrological properties such as prophase soil holding water capacity θ_i, the depth L_i of infiltration affecting and the ratio of $\frac{I_1}{I_2}$ relationship. The change of the ratio $\frac{I_1}{I_2}$ with rain fall conditions determines the speed of the advancing process of soil wetting peak. As the infiltration front advances, the infiltration water gradually changed from channel flow to capillary flow system with increasing negative pressure.

The spatial variation of soil water content is mainly studied in horizontal (x or y) and vertical (z) directions. In the horizontal directions (x or y) of sandy topsoil, there are differences in surface crust, psammophyte cover, herb and shrub cover, macro topography (dune and interdune lowland) and micro topography (concave and convex), due to water repellency of the surface of the crust, litter water imbibition, and highland water delivery and lowland water collection, all the above form source and reservoir water movement

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DOI:10.26502/ijpaes.4490163

Table 2: Comparison of infiltration characteristics of soil free gravity water and capillary water.

Water permeability of underlying surface	$I_1 = \frac{\theta_s - \theta_f}{\theta_s}$	$I_2 = \frac{\theta_f - \theta_i}{\theta_s}$	The thickness L_i of soil reached by the infiltration front
Completely impermeable (dense clay)	$\theta_f \to \infty, I_1 \to 0, P \to R$ (Rainfall P is almost all converted into surface runoff R)	Under impervious environment conditions, water diffusion capacity is saturated $I_2 \to 1$	$L_i \to 0$, Precipitation course has little effect on infiltration.
Fully permeable (sand)	$\theta_f \to 0, I_1 \to 1, P \to F$ (Rainfall P is almost all converted to groundwater F through infiltration)	Water diffusion capacity of soil under fully permeable condition $I_2 \to 0$	$L_i \to \infty$, The soil layer is influenced by the rainfall duration and The gravitational underwater shifting front is pushing downward continuo usly.
Soil permeability between completely impervious and completely permeable	varies with soil type and soil depth, and the amount of infiltration shows a coupling change process with prophase soil water content (θ_i), rainfall process and change ($0 \le I_1 \le 1, 0 \le I_2 \le 1$)		The soil layer L_i is affected by the change of rainfall duration and ($I_L = I_1 + I_2$), and the displacement of infiltration front is a function of prophase soil water content θ_i, rainfall process and *IL* changes

process, therefore, leading to the spatial variabilities of soil infiltration process and water storage. In soil profile of vertical direction (z), the topography of the underlying strata of sand, mezzanine, eolian dune deposition, the transitional characteristics of underlying fine sand strata and palaeosoil interbedded soil, etc. come into being sandy layers of different thickness and the differences of the development of soil profile (Table 3). Because soil mechanical composition at different depths and in different directions affects soil water infiltration and storage capabilities (see Figure 5), which results in spatial variability of the relation and transformation between soil water and groundwater.

Analysis on the Basic Principle of Shrub Forest Evapotranspiration in Sandy Land

In arid and semi-arid sandy land in western China, the precipitation in growing season should firstly meet the water deficit caused by soil drought. In particular, deep seepage rarely occurs in the areas or dunes that have no hydraulic connection with groundwater, but there is subsurface lateral runoff (flow in soil) that rapidly absorbs precipitation, except in some local areas where deep seepage can occur under the control of gravity due to the channel flow with continuous large pores. In the areas or lowlands with hydraulic connection with groundwater, and in the areas with lateral recharge, water in the saturated water layer of soil rises to the active layer of plant roots through capillary action, which is the bridge to the groundwater. Defining:

Soil gravity water storage capacity of rainfall infiltration in sandy landis that free gravity water can be generated only when rainfall infiltration through soil aeration zone (L_i) is greater than field water capacity. Therefore, gravity water storage capacity is the difference between soil saturated water content and field water capacity:

$$V_{s-f} = L_i q_i (\theta_s - \theta_f) \quad (7)$$

Sand soil suspended water storage capacity with rainfall infiltration is that the field water capacity of soil layer above the infiltration front of sandy soil:

$$V_f = L_i q_i \theta_f \quad (8)$$

Soil deficit storage capacity with rainfall infiltration in sandy land:

$$V_{f-i} = L_i q_i (\theta_f - \theta_i) \quad (9)$$

Of all the above, V_{s-f} (mm) is the gravity water storage capacity of the infiltration soil layer L_i (mm), which is generally the catchment source of the areas hydraulically connected with groundwater, lowlands and lateral recharge with interlayers. $\theta_s$is the volume percentage of saturated water content of the infiltration soil layer (L_i), and q_i (g/cm^3) is the bulk density of the infiltration soil layer (L_i). V_f (mm) is the field water holding capacity of wet sand layer under the protection of dry sand layer. With the increase of soil depth (L_i), generally, the percentage of soil fine sand increases, and resulting in the increase of upper soil lateral infiltration catchment sources, but there is also a reduction of $V_f$in the underlying coarse sand layer. θ_f (mm) is the field water holding volume percentage of infiltration soil layer (L_i). V_{f-i} (mm) is the soil deficit storage capacity of the infiltration soil layer (L_i), generally refering to dunes and flat sandy land without hydraulic connection with groundwater, and θ_i (mm) is the percentage of natural water content volume of the infiltration soil layer (L_i).

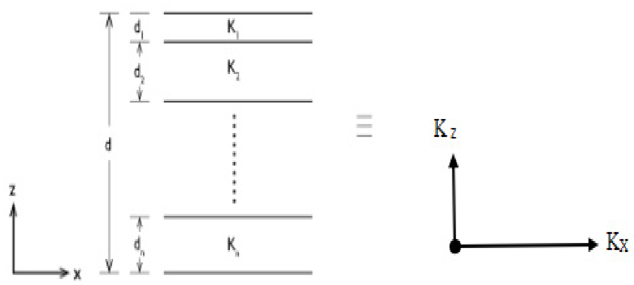

Figure 5: Diagram of the relationship between interlayer heterogeneity and anisotropic heterogeneity

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Large areas of exposed sand, no hydraulic connection with groundwater, and the micro-topography of the sandy land surface was artificially transformed to create shrubbery. Due to the abundant lateral runoff in the sub-surface of the sandy land during rainfall, a collection reservoir was formed on the sandy land (lateral gravity water supply). These soil hydrological phenomena showed that the heterogeneity of water deficit in sandy soil profile is mathematically described as a complex plane, in which the imaginary number and the real number unit 1 are vector identifiers of opposing properties, and the negative and positive signs are quantitative identifiers of opposing properties. The point of the imaginary numbers is that they form a vector space together with the real numbers. As can be seen from Table 4, if the connotation of real unit 1 assigned to soil water storage capacity is dispersion, and the connotation of imaginary unit is polymerization, dispersion and polymerization cannot be identified simultaneously (see Table 5).

Similarly, the fictitious storage capacity for soil saturated water content, field water capacity and soil natural water content in sandy land is respectively : $V_s i = Pq_i\theta_s \times i$, $V_f i = Pq_i\theta_f \times i$ and $V_i i = Pq_i\theta_i \times i$ etc. as pure imaginary number capacity. After the pure imaginary number capacity is spread out, the corresponding relationship shown in Figure 6 exists in the real number storage capacity ($-V_{s-f}(1), V_{s-f}(2), -V_{f-i}(1), V_{f-i}(2)$):

On a sandy land, water consumption by shrub transpiration is directly proportional to the storage capacity of precipitation absorbed by the sandy land, and inversely proportional to the storage capacity of precipitation output:

$$AET = a\left(\frac{-V_{s-f}(1)-V_{f-i}(1)}{V_{s-f}(2)+V_{f-i}(2)}\right)^b = a\left(\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right)\right)^{2b} \quad (10)$$

Where, a, b are coefficient and index respectively, AET shrub transpiration (mm), accordingly, the relationship between plant water consumption (transpiration) and soil water content can be established.

Natural soil moisture in sandy land varies with different landforms, the primary productive forces were distributed in blocks relying on the water characteristics of different geomorphic positions, as a result, the biomass produced in

It can be summarized as follows:

Surface infiltration path	**Heterogeneity of land cover in sandy land**	**Uniformity of land cover in sandy land**
Dry sand layer on the surface	At a certain spatial scale, the surface dry sand thickness distribution is not uniform.	At a certain spatial scale, the thickness of dry sand layer is uniform.
The surface of the crust	At a certain spatial scale, due to the unconformable contact with bare sandy land, in the early stage of rainfall, it becomes the gathering water source for bare sandy land.	At a certain spatial scale, rill erosion is formed and even develops into gully erosion when the rainfall intensity is high because the sandy land t is completely covered by crust.
The ground is covered with litter	At a certain spatial scale, due to the unconformable contact with bare sandy land, it becomes a reservoir of collecting water in the early stage of rainfall.	At a certain spatial scale, due to the full coverage of surface litter, rainfall infiltration is effectively increased, soil evaporation is inhibited, and the thickness of dry sand layer on the surface is reduced.
Subsurface soil infiltration path	No hydraulic connection with groundwater	A hydraulic connection with ground water
High ground (source))	The wet sand layer below the dry sand layer becomes water source for the lowland due to the influence of the elevation ratio of underlying terrain . The depth of dry sand layer is deep, and the soil infiltration can reach 100-200cm. The variation of soil water profile is obvious, and the depth of 40-60cm is water active layer. Below 60cm, water content is stable layer and gradually decreases with soil depth.	The wet sand layer below the dry sand layer becomes water source for the lowland due to the influence of the elevation ratio of underlying terrain. Soil infiltration reaches unsaturated or saturated capillary water rising layer. In particular, the soil moisture in the interdune lowland, which is closely related to groundwater hydraulics, can be divided into three layers: frequent active layer, potential water supply layer and relatively stable layer (Groundwater level).
Lowland (reservoir)	The wet sand layer below the dry sand layer becomes water reservoir collected from the highland due to the influence of the elevation ratio of underlying terrain. Shallow dry sand layer , deep soil body and high soil water content in wet sand layer .	The wet sand layer below the dry sand layer becomes water reservoir collected from the highland due to the influence of the elevation ratio of underlying terrain. Shallow dry sand layer, high soil water content of wet sand layer and high groundwater level .

Table 3: The characteristics analysis of rainfall-infiltration paths in sandy land.

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the small area accounted for most of the total biomass of the sandy land, which provided the basis for dune fixation and psammophyte community restoration and reconstruction.

The formula (10) shows the principle of soil water deficit caused by shrub consumption and free gravity water replenished by precipitation, and on the whole, reflecting the mechanism of soil water movement in sandy land (Table 6).

Shrub plants in sandy land have a higher ratio of underground to surface biomass, indicating that the deep roots and horizontal malleability of plants in sandy land enlarged the available soil water space of vegetation under drought conditions, and relatively supplemented the water consumption caused by transpiration. In the process of dune changing from flowing to fixed, the relationship between soil water dynamics after sand-fixing forest formation and actual transpiration and evaporation law of shrub community reflects the water balance of different vegetation coverage and forestation density (Table 7). Afforestation on sandy land intermittently reserving bare sandy land area to collect surface and subsurface soil runoff (or internal drainage collecting source), adopting patch vegetation configuration with low coverage for afforestation method and technology popularization on sandy land is the key to the success of large-scale sand control afforestation.

Table 4: Calculation method of soil water storage capacity replenished by rainfall infiltration in sandy land.

water storage capacity	$P = \frac{L_i}{\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right)}$ Taken the depth of infiltration as the independent variable)	$L_i = -\frac{P}{\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right)}$ Taken rainfall as the independent variable)
	$V_{s-f}(1) = Pq_i(\theta_s-\theta_f)\beta\, ln(1-\frac{\theta_i}{\theta_s}) \le 0$	$V_{s-f}(2) = -\frac{Pq_i(\theta_s-\theta_f)}{\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right)} \ge 0$
	$V_f(1) = Pq_i\theta_f\beta\, ln(1-\frac{\theta_i}{\theta_s}) \le 0$	$V_f(2) = -\frac{Pq_i\theta_f}{\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right)} \ge 0$
	$V_{f-i}(1) = Pq_i(\theta_f-\theta_i)\beta\, ln(1-\frac{\theta_i}{\theta_s}) \le 0$	$V_{f-i}(2) = -\frac{Pq_i(\theta_f-\theta_i)}{\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right)} \ge 0$

Afforestation Mode of Low Coverage Sand Fixation

Because the characteristics of infiltration and water storage in sandy land, shrubs with dense afforestation of dune (windward slope) will consume excessive water content of soil layer due to the lack of hydraulic connection with groundwater, and drought will cause vegetation decline and death, affecting vegetation stability and sand fixation effect. For flat interdune land and marshy grassland with hydraulic connection to groundwater, soil water content increases with soil depth, and reasonable shrub or tree species (tree species with high water consumption rate) and planting density can be selected according to sand fixation requirements (Table 8). In general, for the large area of sandy land, the soil moisture is mainly replenished by precipitation in dune or flat sandy land, shrub species with low water consumption should be selected for artificial sand-fixation forest, adopting low coverage or low density afforestation layout format, ensuring soil moisture balance in sandy land, maintaining the stability of vegetation and the effect of sand fixation, and promoting the benign succession of vegetation and ecological restoration. From shifting sand to semi-fixed and to fixed transformation process, after the artificial shrubbery settled on the shifting sand, the underground parts of shrub species preserved although experiencing wind erosion and sand burial have the ability to generate new plants and gradually expand the woodland area. However, for shrubs without this ability, coverage increased by seeding and self-propagation, and the sandy land tended to be semi-fixed. Stable growth of shrub forest, litter covering sand, sand environmental

	$V_{s-f}(1) = Pq_i(\theta_s-\theta_f)\beta\, ln(1-\frac{\theta_i}{\theta_s}) \le 0$	$V_{s-f}(2) = -\frac{Pq_i(\theta_s-\theta_f)}{\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right)} \ge 0$
$V_{s-f}(1) - V_{s-f}(2) = 0$	$V_{s-f}(1) - V_{s-f}(2) = Pq_i(\theta_s-\theta_f)\beta\, ln(1-\frac{\theta_i}{\theta_s}) - \left(-\frac{Pq_i(\theta_s-\theta_f)}{\beta\, ln(1-\frac{\theta_i}{\theta_s})}\right) = 0$ $\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right) = \sqrt{-1} = i$	
$\frac{V_{s-f}(1)}{V_{s-f}(2)} = 1$	$\frac{V_{s-f}(1)}{V_{s-f}(2)} = \frac{Pq_i(\theta_s-\theta_f)\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right)}{-\left(\frac{pq_i(\theta_s-\theta_f)}{\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right)}\right)} = -\left(\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right)\right)^2 = 1$ $\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right) = \sqrt{-1} = i$	
$V_{s-f} = \sqrt{V_{s-f}(1) \times V_{s-f}(2)}$	$V_{s-f} = \left(Pq_i(\theta_s-\theta_f)\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right) \times \left(-\frac{Pq_i(\theta_s-\theta_f)}{\beta\, ln\left(1-\frac{\theta_i}{\theta_s}\right)}\right)\right)^{\frac{1}{2}} = Pq_i(\theta_s-\theta_f) \times i$	
V_{s-f}	$V_{s-f} = V_{s-f}(1) = V_{s-f}(2) = Pq_i(\theta_s-\theta_f) \times i$	

Table 5: Unique pure imaginary expression of aggregate of soil free water storage capacity (V_{s-f}).

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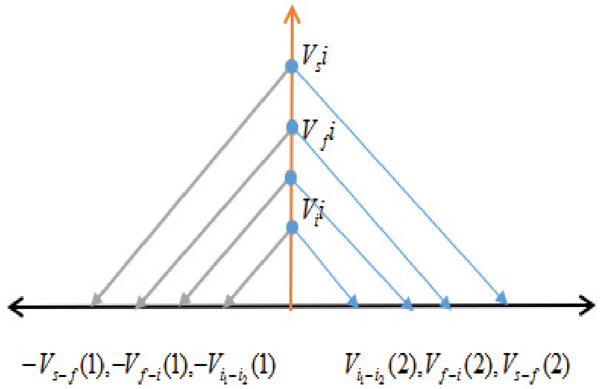

Figure 6: Mapping between pure imaginary storage capacity and real storage capacity of soil moisture parameters in sandy land.

improvement, or to create suitable conditions for the invasion of natural vegetation that increasing vegetation coverage, and shrub communities to further enhance their capability of wind resistance, originally some wind erosion areas gradually occupied by a shrub vegetation, except for the individual sand dune areas, and vegetation joined together making the original quicksand gradually become fixed sandy land. After a certain number of years, the individual growth and reproduction ability gradually declined, the branches died, and the productivity of stand decreased. Most of the afforestation species in sandy land, such as Salix psammophila, Amorpha fruticosa, Hedysarum scoparium, and hettysaruin mongoicurn turcz, can be clipped, and the more clipped, the more exuberant with the characteristics of breeding and growth of tillering. Usually 3-6 years for the first crop replacement and the cropping cycle is 3 to 4 years for harvesting and utilization, and the biomass obtained is large.

A shrub forest with an area of S is set, the aboveground biomass of the shrub forest is GM, the underground root biomass is RM, the soil water content available to the root is SC, the transpiration water consumption of the shrub forest is AET, and the shrub coverage is C_p:

$$\frac{AET}{SC} \propto \frac{RM}{GM}, C_p \propto \frac{\frac{AET}{GM}}{\frac{SC}{RM}} = \rho\left(\frac{RM}{GM}\right)^2 \quad (11)$$

Where, ρ is proportionality constant, $\frac{AET}{SC}$ represents the efficiency of shrub vegetation using soil water storage. If $AET = SC$, representing the balance between soil water storage (collection) and vegetation water consumption in sandy land: $SC = a\left(\beta \ln\left(1-\frac{\theta_i}{\theta_s}\right)\right)^{2b}$,this formula clearly shows that SC depends on the contrast relationship between free water and soil water deficit in the soil profile of sandy land (see Figure 6), and it is a function of shrub root width (root depth and width), precipitation and soil drainage supplement (Table 9).

$\frac{SC}{RM}$ represents the amount of soil water resources used by per unit root biomass and reflects the ability of shrub roots to collect soil water and groundwater and the water catchment area of open sandy land (or shifting sandy land) to be retained. AET is a function of precipitation, temperature, humidity, wind and other meteorological factors. $\frac{AET}{GM}$ represents the transpiration water consumption per unit aboveground biomass, namely the impact of shrub coverage or density on soil water consumption. The root-shoot ratio $\frac{RM}{GM}$ (or crown-root ratio $\frac{GM}{RM}$) is the ratio of the biomass of the root system of the underground part to the aboveground part, which reflects the ecological type of the shrub community under arid and semi-arid climate conditions (Figure 7). The vegetation coverage C_p of afforestation in sandy land can be determined by the square of root-shoot ratio.

The area covered by shrubbery is A, $A = S \times C_p = \rho S\left(\frac{RM}{GM}\right)^2$, $dA = \left(\rho S d\left(\frac{RM}{GM}\right)^2\right) \cdot \left(1 -\right.$, intergal : $\int \frac{dA}{1-\frac{A}{S}} = \rho S \int d\left(\frac{RM}{GM}\right)^2$, $-S\ln(S-A) = \rho S\left(\frac{RM}{GM}\right)^2 + C$, let, $A = 0, C = -S\ln S$,

plug in to: $A = S\left(1 - e^{-\rho\left(\frac{RM}{GM}\right)^2}\right)$, open sand (or quicksand) area :

$S - A = Se^{-\rho\left(\frac{RM}{GM}\right)^2}$

Then

$$C_p = 1 - e^{-\rho\left(\frac{RM}{GM}\right)^2}, \quad 1 - C_p = e^{-\rho\left(\frac{RM}{GM}\right)^2} \quad (12)$$

Table 6: Relationship between rainfall infiltration and recharge in sandy land.

$\frac{V_{s-f}(1)}{V_{s-f}(2)} = 1$	**Characteristics of soil moisture in sandy land**	**Bare sandy land**
Before the precipitation	Under the protection of dry sand layer, the moisture of sub-surface wet sand layer remains stable θ_f.	Dry ground litter, dry sand layer,and to different degrees soil moisture deficit $\theta_f - \theta_i$.
After a little rain	The wet sand layer can reach saturation in a short time, and the channel flow in the soil body developing I_1.	In addition to supply from rainfall infiltration, there is also free gravity water supply from exposed sandy soil $\theta_s - \theta_f$.
After sufficient rainfall	After the wet sand layer reaches saturation $> \theta_s$in a short time, the channel flow I_1 in the sand body is fully developed. The wet front L_i moves down in the (x,y or z) direction.	When the wet sand layer replenished by rainfall and lateral flow reaches saturation $> \theta_s$, channel flow develops I_1 in the sand layer, and the wet front L_i can move downward continuously.

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A Case of Study

Haloxylon ammodendron lives for a long time in the desert, up to 100 years, and being a very good sand-fixing shrub. Haloxylon ammodendron's roots can live in a Chinese herbal medicine called Cistanche, and it is a plant with high economic benefits among sand irrigation plants. However, it is difficult for other psammophytes to exist in the place where a single covering of the ammosault tree dominate a lot of water in the soil, so there will be the risk of ecological imbalance, and a variety of shrubs should be planted mixed (Table 10).

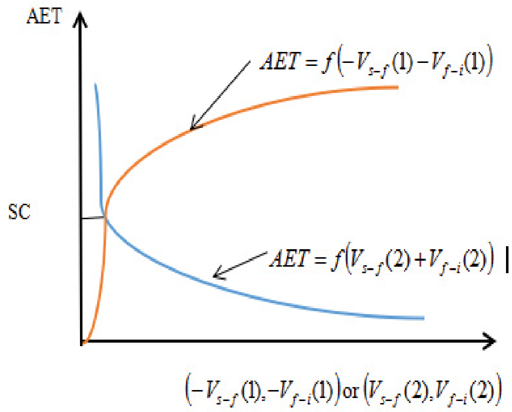

Figure 7: Relationship between transpiration and soil moisture parameters of shrubbery on sandy land.

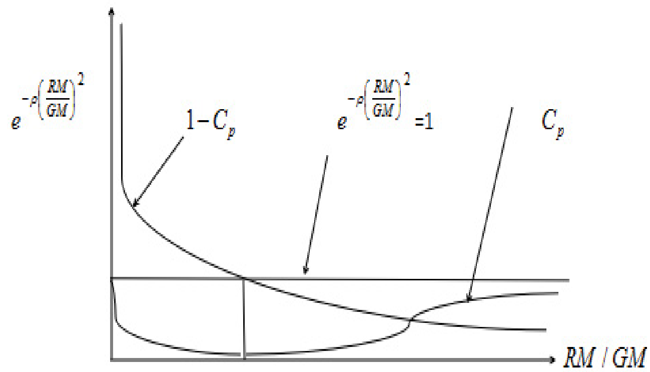

Figure 8: Diagram of relationship between shrub coverage and root-shoot ratio

Table 7: The biological and ecological characteristics of several important shrubs planted in sandy land in northwest China.

Territory	Mu Us sandy land		
Tree species (root-shoot ratio)	**Adaptation**	**Vegetative characteristic**	**Reference**
Salix psammophila (0.5--0.56)	Drought resistance, sand resistance, cold and heat resistance, also like humidity, salt alkali resistance and adapting moderate sand bury.	Psammophila is a typical mesophyte shrub or small tree in steppe area. It is easy to reproduce, the root system developed, strong tillering ability, fast growth rate and lush branches and leaves.	[8, 9]
Amorpha fruticose (0.99--1.84)	Resistance to waterlogging, barren and salt and alkali.	Strong tillering ability and fast growth.	[10]
Sabina vulgaris Ant Sandy land: 0.0278--0.055 highland: 0.0428--0.070)	Be resistant to cold, drought and barren.	Evergreen shrubs, reproduction and sprout strong, creeping growth, covering the ground and root system developed.	[11,12]
Hedysarum scoparium (0.190--0.428)	Cold and hot resistance, suitable for quicksand environment, sand burying resistance, wind erosion resistance	Light - loving, drought - tolerant, strong tillering ability, developed lateral root system, large root width, repeated cloning and growth, connected into a homologous strain and playing a good role in sand fixation	[13]
hettysaruin mongoicurn turcz (0.269--0.638)	Natural sand-bearing shrubs, excellent tree species of windbreak and sand fixation	Having stringing root germination ability, growing fast, often having a plant to become a forest, seed flat, afforestation seeds being not prone to displacement an high germination rate.	[14]
caragana microphylla (0.304--0.429)	Cold, drought, heat, salt and alkali resistance are relatively strong, and a shrub of caragana korshinskii can consolidate soil 23m^{3and} effectively reduce soil wind erosion	It is a deep-rooted tree species, with obvious taproots and lateral roots extending horizontally around, criss-crossing and strong sand-fixing ability. It is not afraid of sand burying. The more sand buried, the more branches, the more flourishing growth, and the stronger sand-fixing ability	[15, 16]

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Artemisia ordosica (0.32-0.53)	Drought resistance, sand burying resistance and resistance to soil barren. The sexual and asexual reproduction of A. orniflora are good, which made it a stable group construction species in arid sandy land.	It has a straight and well-developed root system, which is mainly distributed in the soil layer 20~45cm deep in the semi-fixed sandy land. On the mobile sandy land, the root system can reach 100cm and sometimes 200cm. Artemisia orartemisia on sand after engraftment, with sand fixed, the soil structure changes gradually, such as soil compactness increase and the surface crust produced, etc., Artemisia ordosica gradually becomes inadaptable to its own changed environmental conditions, and its growth becomes poor growing. Although the number of plants is sometimes large, generally short stature with more dry branches and weaker resistance.	[17]
Territory	**Horqin sandy land**		
caragana intermedia (0.99)	Cold and drought and barren resistance, not resistant to waterlogging, more growth in gravel soil, which at the base can be aggregated into small sand dunes. Slight sand burying can promote seedling growth to produce adventitious roots and form new plants.	The aboveground part grows slowly in the early stage and rapidly in the late stage.The first two years of seedling growth belong to the vegetative period, during which the root system mainly grows, The growth of the overground part is very slow, and the depth of the root system into the soil can reach 2 or 3 times of the height of the overground part. In the third year, the growth increases rapidly, and a large number of branches begin to form thickets with thick branches and leaves. When conditions are good, they can blossom and bear fruit, but they generally start to blossom after the fourth year. For promoting the normal growth of C. intermediate, it is generally necessary to clipp one time for renewing every 10 years or so.	[18]
Artemisia wudanica (0.0158--0.0398)	Strong drought resistance, wind resistance, growing in the quicksand and semi-fixed dunes, pioneer plants of sand fixation with thick and many branches, often formed a large dense clumps, the stems and branches can be used as sand fixation barrier or Knitting basket with.	Artemisia wudanica seed sowing, rainy season sowing in the semi-fixed dune sowing hole, the growth of the seedlings grow neatly, strongly and healthy, and cotyledon and hypocotyl are covered with white hairs for the plane sowing, in the rainy season (mid-late July to mid-August), cut without inflorescence of artemisia branches (or the second year branches) before the rain or after the rain buried propagation.	[19,20]
Territory	**West Ordos Sandy land**		
Potaninia Maxim (The roots are mainly distributed in O~30cm soil. The root-shoot ratio is 0.47, but the root width was 6~8 times of the crown width).	Ancient remains of the single species of plants, second-class national key protection plants grow in sandy desert and strong drought resistance and salt and alkali resistance.	Vegetative propagation is mainly carried out in two ways: one is that the stem bends to the surface and is covered by the surface floating sand to form adventitious roots and shoots from the stem tip to form new plants and can be transplanted; the other is split growth, when the plant grows to a certain stage, from the base of the stem up or down several longitudinal cracks, forming a number of independent plants, and finally forming a ring cluster.	[21,22]
Tetraena mongolica Maxim (0.19--0.38 The ration of root to shoot increases with the increase of soil moisture)	The growing soil environment is stony and gravel calcic desert soil and dry and barren soil.It is one of the founding species of vegetation in alxa grassland in China, also as dominant species or associated species listed as a national class A protection plant.	Tetraena is a small shrub with low and strongly small branched branches, a strong xerophyte with a strong root system. The wood is hard and brittle and the radius of 21 year old branches is only 4.4 mm thick. Propagated by seed and layering technology：spreading the branches in a large area, so that tetraena wood to absorb more water, which shows the obvious effects on the growth and breeding of tetraena wood and the cutting technology.	[23,24,25]

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zygophyllum xanthon ylon (0.124--0.500）	Drought-resistant, cold-resistant and barren tolerant, adaptable, quick-growing high-yielding,and strong xerophytic small shrubs , Xerophytic shrubs are the main plant species in the grassland of arid desert area, which can form stable dominant community.	The germination rate of seeds is 90%, the seedlings survive in the arid desert area grow fast, not easy to die, and plant life of more than 20 years. zygophyllum xanthonylon grows 3-4 years to enter the strong age and begins to bear a large number of fruit. After the branches were buried by sand, new branches could sprout from the base and adventitious roots were produced. 75% of the roots were concentrated in the 40 cm soil layer, when it was difficult to compensate, the root reached down to the soil layer of the water storage. After the water was used up in the soil, the root grew back toward the surface, which confirmed that the strong xeriscapous zygophyllum xanthonylon survives mainly by sucking surface water.	[26]
Ammopiptanthus mongolicus (0.558-0.901）	It is characterized by drought, cold, wind and sand resistance, strong resistance to stress, developed root system and nodular root. It is an evergreen super xerophyte, which is obviously not in harmony with contemporary climatic conditions, and reflecting that it is a paleocene relicted species endemic to central Asia and the only super xerophytic evergreen broad-leaved shrub species in desert areas of northwest China. It is the first group of rare and endangered species under key protection in China.	The main reproductive mode is seed propagation, while other reproductive modes are difficult to survive, and seed germination requires higher soil water content, so the natural regeneration ability of A. mongolica is poor in the distribution area of water deficiency. However, the seeds, the main reproduction material of A. mongolica, are susceptible to insect pests and bird damage before and after maturity, and less than 5% of the intact seeds actually fall into the soil, resulting in a lack of natural replacement plants of A. mongolica. Artificial promotion of natural community restoration, practice of expanding cultivation area and research on propagation and cultivation technology.	[27]
Territory	**Sandy land in southern margin of Gurbantunggut Desert, Xinjiang**		
Tamarix ramosissima Ledeb (0.60--2.74）	Light tolerant, drought and cold resistant, water and moisture resistant, salt and alkali resistant, developed root system, lateral root horizontal distribution, very broad and many fine roots and wind erosion resistance, and exposed root system can germinate a lot of new branches, very resistant to sand damage and to resistant to pruning and mowing. It is the key plant species to maintain desert ecosystem in arid areas.	In the shady area, tamarix ramosissima can be propagated by means of cutting, sowing and layering, etc. However, the roots of tamarix ramosissima in normal growth have strong germination ability and are resistant to sand burying. After sand burying, a large number of fine adventitious root can germinate at the root neck and branches can also grow up rapidly. Because of this characteristic, tall tamarix sandy mounds are often formed in sandy areas, which become a unique landscape with fast growth and long life span. Under suitable conditions, the average annual growth of young age is 50-80cm, 2-4 3m in 4-5 years, 4-5m in 10 years, and 7-8cm in diameter, and the life span can reach more than 100 years.	[28]
Haloxylon ammodendron (1.28）	Drought resistance, heat resistance, cold resistance, salt and alkali resistance are very strong, the salt content in the stem and branch is up to 15% or so, light-loving, not resistant to shade, rapid growth, dense branches, developed root system, wind prevention and sand fixation ability, known as the desert guardian, it is extremely widely distributed and has great ecological benefits in desert and semi-desert area.	Haloxylon ammodendron has a strong vitality. Its crown is always baked by the sun and torn by the wind, but it nourishes the desert desertliving cistanche. The seed can only live a few hours and is the world's shortest seed life, however, as long as there is water, it can germinate in 2 to 3 hours, it is the world's strongest germination of life seed, through artificial propagation of seedlings, often forming a large area of pure forest in desert areas.	[29]

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Reaumuria soongonica (0.72)	It is one of the zonal vegetation types widely distributed in the desert area of northwest China. It has shallow root system and is extremely drought-tolerant and salt-tolerant, which is of great significance to soil salt-alkali improvement, vegetation restoration and desertification ecosystem stability.	Soil moisture and salt were important factors affecting the composition of R. soongonica community. Higher soil bulk density inhibited the root growth of the community, mild drought stress promoted the accumulation of above-ground biomass, and a certain concentration of soil Ph and soil salt promoted the root growth and biomass accumulation of the community.	[30]

Table 9: Parameter statistics of ammodendron forest coverage (%) model.

Regression Pattern	Regression model parameters	Explanation
$C_p = \rho\left(\frac{RM}{GM}\right)^2 + c$	Correlation coefficient：r=0.524, Constants: $\rho = -24.661;\ c = 26.169$	The correlation coefficient is low, but it accords with the basic principle of afforestation coverage determination in sandy land.
$C_p = 1 - e^{-\rho\left(\frac{RM}{GM}\right)^2}$	correlation coefficient: r=0.522; $\rho = -0.291$	The correlation coefficient is low, but it accords with the basic principle of afforestation coverage determination in sandy land
$C_p = aRM + bGM + c$	r=0.907；a=0.095；b=-0.024; c=2.922	b=-0.024, it is negative, indicating the rationality of the mechanism model of shrubbery afforestation coverage or density.
$C_p = \rho RM^a GM^b$	r=0.951；a=1.112；b=-0.29; $\rho = 0.229$	b=-0.29, it is negative, which further proves the rationality of the mechanism model of shrubbery afforestation coverage or density.

Table 8: The basic characteristics of 45 haloxylon survey plots in Gurbantunggut Desert presented.

Sample plot no.	Area (hm^2)	Density (plants/hm^2)	Total canopy coverage (㎡)	Coverage(%)	Below ground biomass （kg）	Above ground biomass (kg)	Root Shoot ratio
1	0.808	53	16.97	2.1	13.391	14.377	0.93
2	0.816	132	112.45	13.78	145.832	177.348	0.82
3	1	67	53.25	5.33	38.338	43.238	0.89
4	1	81	131.72	13.17	137.469	171.848	0.8
5	1	126	59.31	5.93	27.902	30.439	0.92
6	1	92	89.19	8.92	70.609	86.113	0.82
7	1	87	101.63	10.16	61.81	73.182	0.84
8	1	37	69.89	6.99	74.543	94.157	0.79
9	1	41	89.17	8.92	71.36	88.122	0.81
10	1	61	133.5	13.35	123.279	154.672	0.8
11	1	87	154.37	15.44	159.02	197.685	0.8
12	1	31	74.22	7.42	89.432	117.498	0.76
13	1	61	95.69	9.57	76.765	92.245	0.83
14	1	49	113.09	11.31	111.23	139.088	0.8
15	1	70	161.46	16.15	153.264	194.163	0.79
16	1	37	51.67	5.17	53.636	66.239	0.81
17	1	81	226.7	22.67	271.232	355.766	0.76
18	1	58	35.19	5.52	51.737	62.446	0.83
19	1	100	217.67	21.77	252.102	337.058	0.75
20	1	33	24.36	2.44	15.398	17.624	0.87
21	1	33	27.97	2.8	21.111	24.888	0.85
22	1	24	62.53	6.25	75.556	100.141	0.75
23	1	38	89.1	8.91	117.215	160.034	0.73
24	1	30	80.43	8.04	66.909	84.098	0.8
25	1	168	157.14	15.71	197.166	255.523	0.77

26	1	49	134.94	13.49	148.784	190.041	0.78
27	1	42	112.41	11.24	153.882	213.03	0.72
28	1	132	170.36	17.04	138.623	180.387	0.77
29	1	21	9.35	0.94	9.89	12.169	0.81
30	1	29	15.96	1.6	20.773	25.519	0.81
31	1	15	17.44	1.74	19.393	23.963	0.81
32	1	34	138.22	13.82	162.288	214.681	0.76
33	1	74	207.93	20.79	217.955	275.082	0.79
34	1	32	87.41	8.74	92.146	116.419	0.79
35	1.054	31	49.01	4.65	54.072	64.236	0.84
36	1.056	21	80.53	7.63	76.927	107.599	0.71
37	1.17	33	193.79	16.56	221.901	348.235	0.64
38	1.197	80	268.93	22.47	269.924	381.17	0.71
39	1.2	92	40.5	3.38	22.831	25.406	0.9
40	1.264	63	72.34	5.72	57.328	88.593	0.65
41	1.368	42	103.56	7.57	103.585	116.44	0.89
42	1.54	81	278.19	24.56	404.005	589.996	0.68
43	1.549	39	83.92	5.42	107.106	100.137	1.07
44	1.626	82	282.59	17.38	232.361	414.816	0.56
45	2.255	58	401.91	17.83	416.069	577.992	0.72

Data source: Tao Ye, Zhang Yuanming. Multi-scale estimation of desert shrub biomass: a case study of haloxylon ammodendron, acta prataculturae sinica, 2013, 22 [6]

Table 10: Exhbition of analysis results of regression model for the coverage of Ammodenia forest.

Regression Pattern	Different root-shoot ratios (R/G)	Coverage (C_p) %	Density (plants/hm²)	Single plant covers area (m²)	Rainfed area (1-C_p) %	Rainfed area per plant (m²)
$C_p = \rho\left(\frac{RM}{GM}\right)^2$	0.55	18.71	60	166	81.29	135
	0.75	12.3	60	166	87.7	146
	0.85	8.35	60	166	91.65	153
	0.9	6.19	60	166	93.81	156
	1	1.51	60	166	98.49	164
$C_p = \rho RM^a GM^b$	0.55	17.05	60	166	82.95	137
	0.75	19.83	60	166	80.17	133
	0.85	2.68	60	166	97.32	161
	0.9	2.9	60	166	97.1	161
	1.07	10.88	60	166	89.12	147

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DOI:10.26502/ijpaes.4490163

Summary

Research background

The semi-arid sandy land ecosystem in western and northern China is in the transition zone between sandy and loess regions, arid and semi-arid regions, as well as the interleaved zone between grassland grazing area and agricultural farming area, which is a typical area with fragile ecological environment. The damage caused by wind erosion in sandy soil in arid and semi-arid areas is far greater than the cost of controlling wind erosion. The dust source and affected area of each sandstorm will be damaged by wind erosion to varying degrees, and the depth of wind erosion of dust source can reach 10cm. It is estimated that the loss of soil fine particles caused by sandstorms in China is as high as 106-107 tons every year. The grain size of most of them is below 10μm, which has caused serious damage to the land productivity of farmland and grassland in the source area. The construction of wind-proofing and sand-fixing forest has always been an important measure of ecological restoration and environmental governance.

Most of the territory of northwest China is covered by shrubs and herbaceous plants. The hydrological ecological research on the community structure, distribution pattern and evolution process of plants under water stress is far from effective guidance for the practice of sand fixation and afforestation. If the drought index series is from P/ETP>1(the ratio of precipitation to potential evaporation) down to < 0.3, the vegetation will evolve from the potential comprehensive coverage to the broken vegetation canopy to the patchy vegetation distribution state. The most significant feature of vegetation in arid zone is low coverage. Since the 1980s, China has carried out large-scale protection forest construction in North China, Northwest China and Northeast China. In the construction of artificial vegetation to prevent and control soil erosion by water and wind, the vegetation coverage design and its configuration have been ignored, resulting in the problems of soil dryness and low stability of artificial vegetation in arid and semi-arid areas. The improper selection of some tree species causes large area loss, such as the production of a large area of soil dry layer, the occurrence of large area of pests and diseases, the phenomenon of "small old tree" and the low survival rate of afforestation.

How to make the limited precipitation be used by vegetation and maintain the water balance of forestland in sandy land? What is the density of vegetation without water deficit? What is the distribution pattern of vegetation dependent soil water environment? How to manage the utilization of water resources and vegetation in sandy land? It is of great significance for vegetation reconstruction, ecological restoration and rapid and efficient control of wind erosion desertification. When the soil is dry or barren, plants preferentially allocate photosynthetic products to the root system, thus changing the ratio of crown to root and strengthening the ability of the root to absorb water and nutrients. Therefore, establishing the correlation among soil water movement, water absorption by roots and water consumption by plants is a new idea to build a model of transpiration and evaporation. This paper was supported by National Natural Science Foundation project "Study on Soil Water Consumption Model of Shrubbery community on Sandy Land", which belongs to part of the research content of this project. In addition, based on the support of this project, the author conducted in-depth research on the existing problems in desertification control and afforestation from the aspects of natural capital, economic capital, scientific and technological capital and social capital, and put forward the plan of Desertification Control and Integrated Ecosystem Management in China.

Main Achievements

Based on Darcy's law and the theory of soil water potential, the characteristics of soil water infiltration in sandy land were expounded comprehensively, deeply and systematically, and the relationship between two different seepage systems of sandy land soil capillary flow and macroporous channel flow and the depth of soil infiltration front and their mathematical models were proposed. Accordingly, a mathematical model of the equilibrium relationship between soil water storage (collection) and vegetation water consumption was derived. In essence, it reflected the correlation between plant root-shoot ratio, precipitation and soil drainage supplement. The vegetation coverage (afforestation density) of shrub on sandy land can be determined by the root-shoot ratio of shrub species. Under dry conditions, the deep roots and horizontal ductility of shrub plants on sandy land expand the available soil water space of vegetation, and relatively supplement the water consumption by transpiration. The above two models illustrate the relationship and transformation between the "source" and "reservoir" of soil water from both qualitative and quantitative aspects, and propose and prove that the technical measures of low coverage water harvesting and forest management are the key to the success of large-scale desertification control.

Theoretical Innovations

The relationship between the capillary flow system and the macroporous channel flow in sandy soil and the depth of soil infiltration front and their mathematical models were proposed for the first time. These hydrological phenomena showed that the heterogeneity of water deficit in sandy soil profile was mathematically described as a complex plane. If the real unit 1 of soil water storage capacity was assigned, the connotation was spread out. The connotation of the imaginary number unit i is polymerization, and both dispersion and polymerization cannot be recognized simultaneously. In view of the corresponding relationship between pure imaginary

Citation: Mingyuan Wang. The Theory of Sandy Land Soil Hydrology and Mode of Low Coverage Afforestation in Northwest China. International Journal of Plant, Animal and Environmental Sciences.14 (2024): 42-58.

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DOI:10.26502/ijpaes.4490163

storage capacity (imaginary storage capacity) such as soil saturated water content, field water holding capacity and soil natural water content and real storage capacity (actual soil water holding and displacement) after spreading out, a mathematical model of the equilibrium relationship between soil water storage (collection) and vegetation water consumption was derived. In essence, it reflected the correlation between plant root-shoot ratio, precipitation and soil drainage supplement. A mathematical model for determining afforestation density (coverage) based on root-shoot ratio was proposed for the first time. The basic principle of low coverage afforestation in sandy land was expounded and the practice of afforestation under sand control was guided. The soil rhizosphere water consumption model and density formula of shrub community on sandy land have clear physical significance and easy parameters to determine, which has universal applicability to the study of vegetation-soil water relationship of plantation forest.

Application Background

Soil erosion and wind erosion are the two main causes of land degradation. They have caused 84% of the degraded land area in the world. This natural process combined with excessive erosion caused by human activities has become one of the most serious environmental problems in the world. In China, "State specially stipulated shrubbery forest" refers to the shrubbery economic forest which is distributed in arid and semi-arid areas with average annual precipitation less than 400 mm, or above the upper limit of tree distribution, or in tropical and subtropical karst areas, dry hot (arid) river valleys and other ecological and environmental fragile areas, and is operated for protection purposes and economic benefits. Shrub land, including the construction of artificial shrub land and the protection of natural shrub land, is the key problem of how to use the limited water resources of sandy land in arid and semi-arid areas to improve the vegetation coverage and prevent the damage of wind sand.