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RESEARCH ARTICLE

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Soil water carrying capacity of vegetation in the northeast of Ulan Buh Desert, China

Abstract The dynamic change of soil water as a function of leaf area index and the soil water deficit value, prerequisites for assuring the survival of plants, were simulated. We established a dynamic soil water model based on a theory of water balance, the characteristics of the environment, and the physiological ecology of the plants in the Ulan Buh Desert, northwestern China. We estimated the soil water carrying capacity of the vegetation in our study area of the desert. The results showed that the proportion of soil evaporation in the total amount of precipitation was greater than 60% in the wandering and semifixed sands and 44.8% in the fixed sand. When the leaf area index was less than 1.7 m^2/m^2, the soil water deficit was maintained at a low level, but when the leaf area index continued to increase, the soil water deficit increased rapidly as well. In consequence, we come to the conclusion that the leaf area index of the soil water carrying capacity of the vegetation is 1.7 m^2/m^2 in our study area.

Keywords Ulan Buh Desert, soil water deficit, soil water carrying capacity of vegetation, leaf area index

1 Introduction

The Ulan Buh Desert is one of the eight largest deserts in China. The northeastern area occupies 1/3 of the total area of this desert (Ji, 1999) where active intervention in the composition of the vegetation is the main method for combating desertification (Liu et al., 1996; Su et al., 2004). This area has a fairly good environment and a long history of agricultural development, and the water condition is relatively superior to the rest of the Ulan Buh Desert. We should consider and discuss how to use the limited water resource for the establishment of vegetation in environmental rehabilitation. In the study of the soil water carrying capacity of vegetation, more and more attention has recently been paid to this aspect of saving the desert. It is part of the study on the relationship between vegetation and soil water because the establishment of vegetation in arid and semi-arid areas, on soils degraded to a large extent by an increasing incidence of severe droughts in the plantations and grasslands in this arid region of northern China requires drastic intervention (Ma et al., 2001; Guo and Shao, 2004). There are a number of methods provided to calculate the soil water carrying capacity of vegetation. Guo and Shao (2003, 2004) define the soil water carrying capacity of vegetation as the maximum density of healthy growing plant communities that can be maintained with the soil water absorbed and used by the roots, where its consumption is equal to or less than the water in the soil layer of the roots supplied by natural precipitation in the course of a year or more. Ma et al. (2001) proposed that the maximum carrying capacity of soil water by tree species can be calculated from the ratio of the gross amount of available soil water to individual water consumption. At present, measurement of soil water carrying capacity of vegetation continues to use the traditional unit (i.e., tree density) (Verplancke et al., 1992; David, 1999; Ma et al., 2001; Yan et al., 2001; Gao et al., 2002; Zhou et al., 2002; Deng et al., 2003; Guo and Shao, 2003; Wang et al., 2005; Radersma et al., 2006). Maintaining the water balance is the most important condition for keeping the stability of the forest vegetation ecosystem in arid and semiarid areas (Yu and Chen, 1996). If the vegetation consumes too much of the soil water, the water balance of the vegetation ecosystem becomes disturbed, the soil degenerates, and the environmental conditions deteriorate. Thus, the core of our investigation in the soil water carrying capacity of vegetation should emphasize the relationship between the vegetation and the water resources, based on the water

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balance of the vegetation ecosystem. That is to say, it concerns the study of the maximum carrying capability of the soil water of the vegetation, on the precondition that the vegetation maintains or improves the water resources.

Therefore, given our objective of studying the relationship between soil water and vegetation, we have measured the characteristics of physical soil properties, soil water, vegetation, and plant ecophysiology since 2003. Based on the theory of water balance, a dynamic soil water model is established. After that, the soil water carrying capacity of vegetation is studied in this area to provide a theoretical basis for solving the contradiction between available water resources and the resumption of vegetation restoration. The vegetation in the Ulan Buh Desert was mainly composed of shrubs with conjunctive roots and plants that cannot be divided into the individuals. Moreover, a stable ecological system can exist only when the relationship between the structure and amount of vegetation is satisfied. In our study, we have used leaf area index (LAI), which is directly related to transpiration, as the index for evaluating the soil water carrying capacity of vegetation.

2 Site description

Our study site lies on the eastern border of the arid desert in Northwestern China. It is the northeast of the Ulan Buh Desert, located southwest of the Houtao plain in the middle of the Yellow River catchment area and between the Lang Mountain and Yellow River in Inner Mongolia (40°09′–40°55′N, 106°09′–107°10′E), at an elevation of 1030–1077 m, where the topography of the northwest is higher than that of the southeast. This area has a desert climate in the temperate zone in Asia that is cold, dry, and windy, with little rain, which falls mainly in the summer and autumn, and has the characteristics of a continental climate and monsoon rain. At the site, the amount of precipitation is small, it lasts for only a short time, and evaporation is great. The mean annual precipitation is 105 mm, and the evaporation was 3041 mm from 2000 to 2006. The experimental plots were in the alluvial plain of the old riverbed deposited by the main lake. The deposits consist of the interplay of loam sand, mild clay, and fine sand and have been covered with eolian sand in more recent times. The zonal soil is a gray desert soil, which is dry and poor. The change in soil texture among the experimental plots and in a vertical direction is small. The changes in the level of soil water are insignificant between different years, whereas it varies more among different months; it is correlated with precipitation. The vertical change of the soil water occurs mainly in the soil layer above 80 cm (Ye et al., 2005).

The site lies in the transition zone from the desert steppe to a grassland desert with typical desert features. The species are arid shrubs, subshrubs, and psammophytes; the dominant species are *Nitraria tangutorum*, *Ammopitanthus mongolicus*, and *Artemisia ordosica*. The vegetation is sparse, and the structure is simple. The relationship between LAI, coverage of vegetation, and biomass shows positive correlations (He et al., 2005a).

The experimental plot is a wandering dune (area 1.53 km^2), a semifixed dune (area 0.25 km^2), and a fixed dune (area 0.10 km^2) outside the oases and lies in a direction from north to south. A latticed dune and chain dune, present in the wandering dune, and the interdune area together account for 18.5% of the total area. The dominant species is *N. tangutorum*, which grows on coppice mounds. The height of the dunes is usually 3–7 m, whereas several are higher than 7 m. The groundwater level is 4.5–11.5 m in the wandering dune. The geomorphological characteristics of the semifixed dune show a different distribution of coppice mounds of *N. tangutorum*. The soil of the interdune area is clay. The height of the coppice mound of *N. tangutorum* is usually 1–3 m. The groundwater level is 3.7–10 m. The fixed dune has a clay soil, covered with sandy soil where the dominant species are *A. mongolicus*, *A. ordsica*, and *N. tangutorum*. The groundwater level is 2.7–3.5 m.

3 Study methods

3.1 Sample plot investigation

Six fixed plots were established in the wandering dune, composed of interdune areas and the wandering dune. Because the water conditions in different places and the moving characteristics of the dune are affected by changes in seasonal wind directions, eight sampling belts were established in the eight directions of the wandering dune. A sample belt was 2 m in width, and the lengths varied from the center of the interdune area to the top of the dunes around the interdune. The soil samples are taken from the top, the middle, and the bottom of the wandering dune and the interdune area. Coverage and the biomass of all the plants were studied within the sample belt, whereas those of *N. tangutorum* on the entire site were understudy. The 5 m × 5 m sample plots were set at the intersection and four apices of the diagonal in the semifixed dune and the fixed dune. Soil samples were taken at the center of the plot, and all the plants in the plot were investigated. The vegetation characteristics of the plots are shown in Table 1.

3.2 Dynamic soil water model

Based on a theory of water balance, the relation among the soil water content, C_{t2} and C_{t1}, at time t_2 and t_1 in the root layer (0–120 cm), the water supply in period t, S_w (mm), where $t = t_2 - t_1$ and the water consumption C_w (mm) can be described as follows: $C_{t2} = C_{t1} + S_w - C_w$. It is the

Table 1 Vegetation characteristics of plots

plot	dominant species	coverage/%	biomass/(kg·m^{-2})	LAI/(m^2·m^{-2})	coverage of dominant species: coverage of vegetation/%
fixed sand	*A. mongolicus*, *A.ordosica*, *N. tangutorum*	33	0.179	1.56	81
semifixed sand	*N. tangutorum*	24	0.156	0.22	99
wandering sand	*N. tangutorum*	6	0.064	0.14	95

basic expression of a dynamic soil water model, in which C_{t1} is the simulated initial value of soil water. The soil water in the root layer is derived from rain on the site and because the vegetation is sparse, the wind is strong, and the time of precipitation is short, the canopy interception is small, and more than 97% of the rain arrives at the soil surface where the depth of infiltration is less than 120 cm (Ye et al., 2005). Thus, S_w is approximately equal to the precipitation in period t. The soil water consumption C_w (mm), in period t is composed of soil evaporation E (mm), vegetation transpiration T (mm), and direct runoff R (mm) in period t. E and T can be calculated by the Penman-Monteith equation (PM equation) (Shuttleworth and Wallace, 1985; Verplancke et al., 1992; Yan et al.; 2001; Gao et al., 2002; Zhou et al., 2002; Cheng and Chen, 2003).

The water evaporation E_0 (mm):

$$E_0 = (\Delta A + \gamma E_a)/(\Delta + \gamma) \tag{1}$$

Soil evaporation E (mm):

$$E = (\Delta A_q + \gamma E_a)/[\Delta + \gamma(1 + r_{ss}/r_a)] \tag{2}$$

Plant transpiration T (mm):

$$T = (\Delta A_s + \gamma E_a)/[\Delta + \gamma(1 + r_{sp}/r_a)] \tag{3}$$

where Δ is the slope of the saturated vapor pressure-temperature (kPa/°C); A, A_s, and A_q are the net daily radiation of water, canopy, and ground (mm/d), respectively; γ is the psychometric constant (kPa/°C); r_a is the aerodynamic resistance, which relates to the boundary layer characteristic and the wind; r_{ss} and r_{sp} are the stomatal resistance and the conduct resistance of soil water, respectively; and E_a is the drying power of the air (mm/d).

$$E_a = C_p\rho/(\lambda\gamma) \times D/r_a \tag{4}$$

where λ is the latent heat of vaporization, ρ is the density of air, C_p is the heat capacity of air, and D is the saturated vapor pressure deficit, which is the difference between the saturated vapor pressure (e_s) and the actual vapor pressure (e_d) at the same temperature.

3.3 Investigation of soil water, soil physical characteristics, and vegetation characteristics

The soil water content is measured by drying. Soil samples are taken by a cutting ring, which has a diameter of 5 cm and a volume of 100 cm^3. The depth of sampling, which varies in different soil types, was 120 cm in the clay of the interdune area, the fixed and semifixed dunes; 100 cm in the sand of the wandering dune and the *N. tangutorum* coppice mounds; and 40 cm in the clay under the sand. Soil samples were taken at intervals of 20 cm from the surface layer, that is, at 20 or 40 cm according to the depth from the ground surface to the center of the cutting ring, except for the surface layer where the depth of measurement was 5 cm. There are 3–5 replications. Measurements were taken in the middle ten days of each month from April to September in 2003–2005.

The bulk density, field capacity, and maximum moisture capacity of the soil were also measured using the cutting ring. The soil water potential was measured by an HR-33T Dew Point Microvoltmeter. The relation between the absolute value of soil water potential (ψ_s) and the volumetric moisture content (x) was described by the exponential functions $\psi_s = 0.175x^{-0.88}$ and $\psi_s = 0.004x^{-1.411}$ in clay and sand, respectively. The average soil saturated hydraulic conductivity (K_s) in clay and sand was 0.000124 and 0.003572 cm/s, respectively, measured by a 2800K II Guelph Permeameter. The unsaturated hydraulic conductivity (K) is calculated by the equation $K = K_s e^{(\alpha\Psi_m)}$, where α was also measured by the Guelph Permeameter, and Ψ_m is the soil water potential, approximately. The relationship between the water conduct resistance of soil (y, d/mm) and the volumetric moisture content (x) is $y = 1.76 \times 10^{-6} x^{-1.40}$ in clay and $y = 8.00 \times 10^{-14} x^{-1.48}$ in the sand, both obtained by experimentation of soil evaporation.

The time of measurements of the vegetation biomass, LAI, ground diameter, height, crown diameter, and other variables coincided with the time of the highest soil water content. In 2003–2005, coverage of the vegetation was investigated once a year in August or September of each of the three years. The biomass was measured by drying and weighing. The leaf area of the broad-leaved trees (*N. tangutorum* and *Ammopiptanthus mongolicus*) was measured by means of standard scale paper (Liao et al., 1990). The leaf area of *A. ordosica* was estimated using the formula:

$$S = \sqrt{4\pi VL} \tag{5}$$

where L is the leaf length (cm) and V is the leaf volume (cm^3), measured by draining.

The transpiration rate, photosynthetic rate, and stoma conductivity of plants were measured by an LI-6400 (America, Li-COR Ltd.). The water potential of plants was measured in a pressure chamber. In 2003–2005, all indices were measured in 2–3 sunny days in the middle of each month from April to September. The measurements were made from 7:00 to 19:00 at 2-h intervals. When vegetation transpiration was calculated by the PM equation, r_{sp} was assigned the minimum value of the daily course in every month (the maximum stoma conductivity), corrected for the relation between the stoma conductivity, light, and plant water potential in the morning (He et al., 2005b).

3.4 Calculation soil water deficit

The critical soil water value C_s (mm) is the lowest soil water content (the soil wilting point) for keeping the plant alive. When the soil water (C_{t2}) is less than C_s, the plant will die. When C_{t2} is greater than or equal to C_s, there is actually no water deficit. The calculations of the soil water deficit (D_s) were conducted when $C_{t2} < C_s$, then $D_s = C_{t2} - C_s$, and when $C_{t2} \geqslant C_s$, then $D_s = 0$. When there were no plants, we assumed $C_s = 0$ because when C_{t2} is greater than or equal to 0, then $D_s = 0$. The soil water deficit W_D (mm) in the period from the beginning to the end of the simulation was: $W_D = -\sum D_s$.

The time interval of the soil water simulation was one day at the site, whereas hours were used in some modules, such as an infiltration model. The statistics of the month and the year were the accumulated day values in the simulation. We have used the average value of the results of the simulation during the 2000–2005 investigations of the water balance, characteristic of vegetation, and the soil water carrying capacity of the vegetation. Given the vertical differences of soil water, the soil was divided into two layers, a surface layer to 20 cm and a second layer from 20 to 120 cm for simulation.

Precipitation and other meteorological data, required in the model, were measured by an Li-1400 data logger. Soil water movements, such as infiltration, were based on Darcy's law.

4 Results and analysis

4.1 Comparison between evapotranspiration and soil water storage

The potential evaporation in the area during the 2000–2005 period, calculated by the PM equation, and the evaporation of the water surface, measured by the weather station, are clearly correlated ($p < 0.01$). The slope of a regression line (b) was approximately 1; a, the intercept was less than the *SD*; and the relative error, which was the greatest in 2000, was 11.5%. It shows that the PM equation can be used to simulate the evaporation of the water surface in the area.

For comparing the relation of soil evaporation between the simulation and the actual measurements, it should be pointed out that the experiment of the soil evaporation of the sand was made using eight soil evaporators (both diameter and height: 20 cm) in the wandering dune from July 14 to Aug 10 in 2004. The initial soil water content, as seen in Table 3, was 23.4%, its maximum water-holding capacity. The other six levels were determined from the range of soil water changes in the 20-cm layer in the experiment plots (Ye et al., 2005). The change of evaporation during a period of drought is shown in Fig. 1. It shows that the daily evaporation decreases as the time of the experiment increases until evaporation approximates zero. The initial soil water content affects the evaporation capacity over the course of evaporation. When the initial soil water content was 6%, the time to approach the asymptotic value, that is, when the rate of evaporation was zero, was more than 22 d, and when it was 3%, the length of time required was about 12 d. The results from Fig. 1 and Table 3 indicate that the relationship between the simulated value and the measured value is marked by a liner correlation with the ($p < 0.01$). The simulated value of soil evaporation can replace the actual value for studying the soil water deficit at the site over long periods.

Liu et al. (1997) and Ju et al. (2000) compared the transpiration with different measurement techniques. It

Table 2 Regression analysis of simulated and actual water surface evaporation

item	year					
	2000	2001	2002	2003	2004	2005
actual water surface evaporation/mm	2850	3269.9	2829.1	2982.2	2982.2	2982.2
simulated water surface evaporation/mm	2970.89	3284.77	2870.18	3066.03	3005.71	3046.04
A	−12.05	−30.41	42.19	−4.38	2.45	16.91
B	1.01	1.11	0.81	0.99	0.98	0.91
R	0.82	0.95	0.97	0.94	0.95	0.95
SD	114.34	63.28	32.42	56.43	52.75	54.68

Note: the regression equation is: $y = a + bx$, the same as in Table 3.

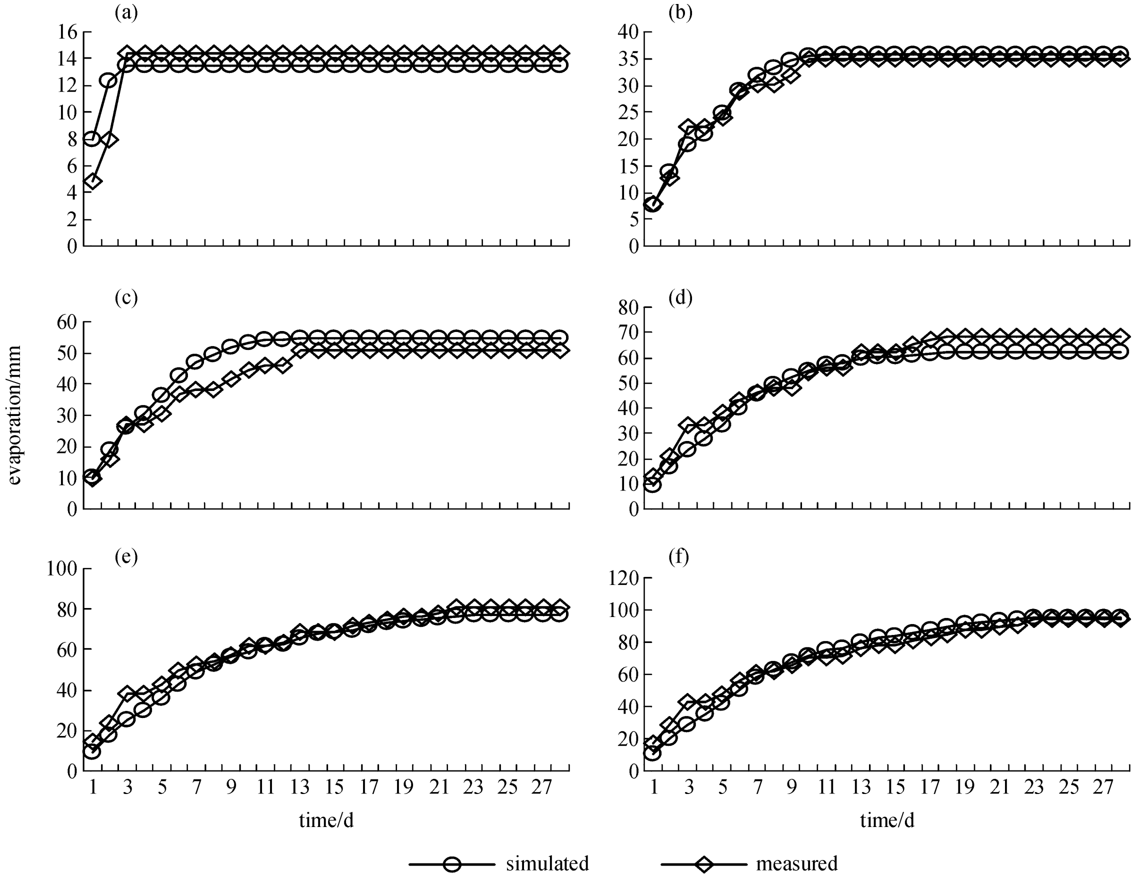

Fig. 1 Changes in soil evaporation from July 14 to August 10 in 2004. (a)–(f) are 1%, 3%, 4%, 5%, 6%, 9% initial soil water content, respectively.

Table 3 Regression analysis of simulated and actual soil evaporation

item	initial soil water content/%						
	23.4	1	3	4	5	6	9
a	−0.552	−0.149	−0.531	−1.875	−0.931	0.110	0.200
b	1.027	1	0.777	1.001	0.616	0.932	1.089
R	0.93	0.90	0.85	0.83	0.91	0.85	0.88
SD	0.935	0.057	0.206	0.104	0.154	0.281	0.262

shows that, although transpiration, simulated by different calculation methods, exhibits variation, they all show significant correlation. The least errors occurred with the Penman-Monteith equation, the heat pulse technique, and a whole-tree photometer. For verifying the accuracy of these results, the simulated value of transpiration was compared with the actual value, calculated from the leaf area, the hours of sunshine, and the value measured by the Li-COR6400. It is shown that the relationship between the two kinds of transpiration is a linear correlation, showing significant correlation ($p < 0.01$), with a regression coefficient approximately equal to 1, that is, the actual transpiration can be simulated using the PM equation to study the transpiration over long periods.

The soil water content has a large effect on the course of water movement, such as the distribution of precipitation in the soil, soil evaporation, and plant transpiration. At the same time, it is affected by the course of the water movement. The accuracy of simulating the soil water storage capacity is affected by a number of factors. The difference between the simulated and the measured value of the soil water storage capacity in the wandering dune is shown in Fig. 3. It shows that they are quite similar. The relative error of the water storage capacity in the first meter of sand is less than 13%. It indicates that the accuracy of simulating soil water storage capacity is quite acceptable.

Based on these comparisons of the main parameters (soil evaporation, plant transpiration, and soil water content)

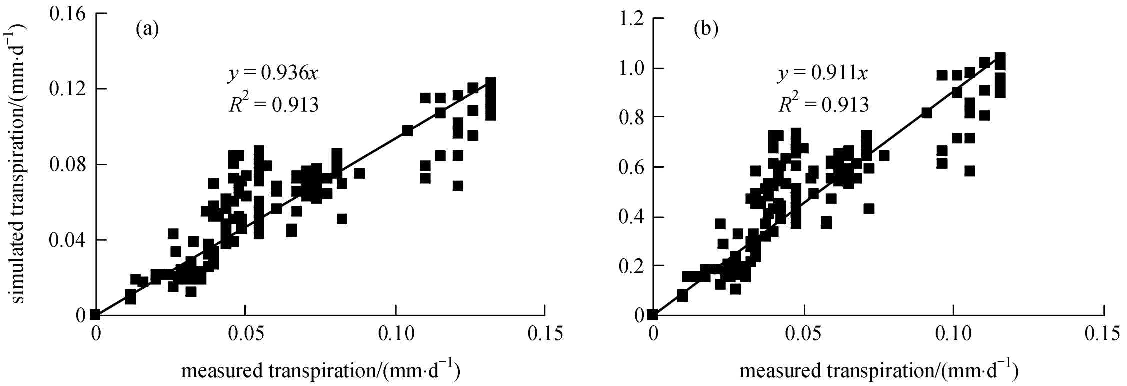

Fig. 2 Relationship between measured and simulated transpiration. (a): *Ammopiptanthus mongolicus*; (b): *Artemisia ordosica*.

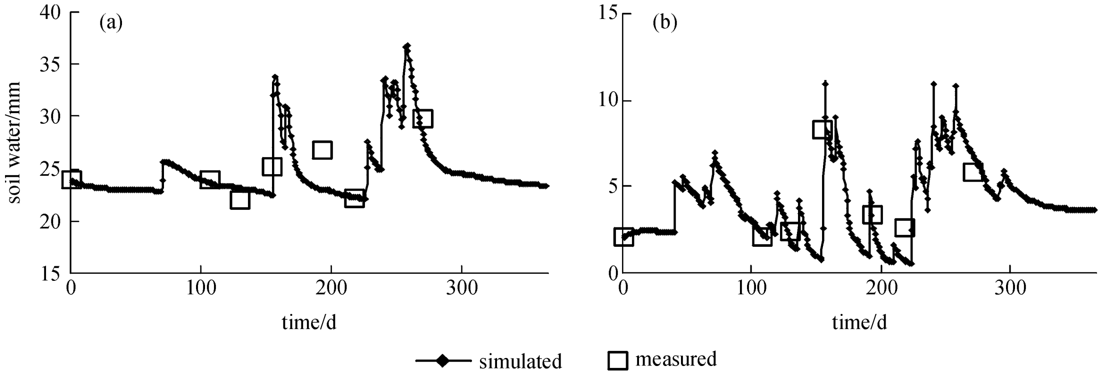

Fig. 3 Soil water storage by simulation and measurement. (a): soil layer in 20–100 cm; (b): soil layer in 0–20 cm.

between the actual measurements and the dynamic soil water model, the parameters in the model were calibrated, and the soil water storage capacity was simulated by the model on the sand for the period 2000–2005. As well, characteristics such as soil water and composition of evapotranspiration in the Ulan Buh Desert were studied on the basis of the average values of the six years (Table 4).

It shows that soil evaporation is greater than plant transpiration on all sites, that the soil water storage capacity and the proportion of evaporation in the precipitation decrease, and that the proportion of transpiration in the precipitation increases as the vegetation cover and LAI increase (Table 1). The simulated results are consistent with the results obtained by He et al. (2005a).

4.2 Relationship between the soil water deficit (W_D) and LAI

Figure 4 shows that, on the whole, the soil water deficit (W_D) on the site increases with an increase in the LAI. When the leaf area index varies in the range from 0 to 1.7 m^2/m^2, the variable rate of W_D is less than or close to zero. It indicates that the soil water condition can satisfy the requirements of the vegetation. When the leaf area index is greater than 1.7 m^2/m^2, W_D increases exponentially and rapidly with an increase in LAI. This indicates that the soil water condition cannot satisfy the requirements of the vegetation. There is clearly a critical point, in which the maximum LAI (LAI$_{\text{max}}$), when assuring normal

Table 4 Soil water and evapotranspiration in Ulan Buh Desert

Item	fixed sand	semifixed sand	wandering sand
soil water deficit/mm	0.059	0.069	0.496
soil water storage in 0–20 cm/mm	19.0	20.7	26.9
soil water storage below 20 cm/mm	69.6	80.3	160.4
annual transpiration/mm	43.1	10.3	6.9
annual soil evaporation/mm	47.1	64.5	73.8
ratio of transpiration to precipitation/mm	41.0	9.8	6.6
ratio of evaporation to precipitation/mm	44.8	61.3	70.1

Note: Annual precipitation was 105.2 mm.

growth of vegetation in satisfying its condition of the water balance, could be ascertained from the relation of changes in the soil water deficit with changes in LAI. According to Fig. 4, the $\mathrm{LAI}_{\max}$ at 1.7 $\mathrm{m}^2/\mathrm{m}^2$ is almost the same in the wandering dune, the fixed dune, and the semifixed dune.

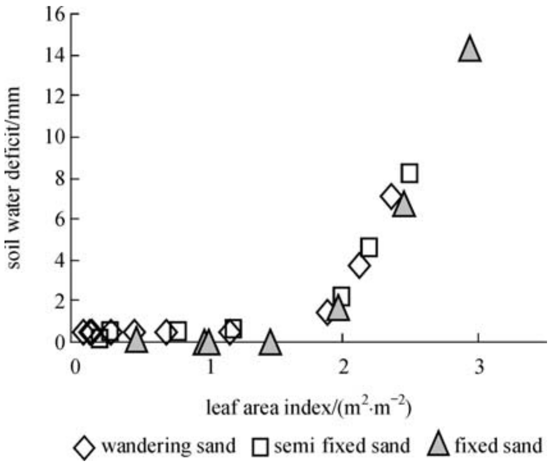

Fig. 4 Relationship between soil water deficit and leaf area index (LAI)

5 Discussion

Because shrubs are the main components of the vegetation in the Ulan Buh Desert, it is difficult to obtain measurements of different individuals and to estimate the soil water carrying capacity of the vegetation on a number of individual plants on the site. The LAI shows a linear relation with the vegetation coverage in the Ulan Buh Desert (He et al., 2005a). The soil water storage capacity decreases with an increase in the LAI, and there is an internal relation between LAI and soil water consumption. Therefore, we have regarded the $\mathrm{LAI}_{\max}$ as the index for evaluating the soil water carrying capacity of the vegetation. The greater the $\mathrm{LAI}_{\max}$, the greater the soil water carrying capacity of the vegetation. It indicated that, although there is a different vegetation composition in the wandering dune from that of the fixed dune, they have the same soil water carrying capacity of the vegetation, that is, $\mathrm{LAI}_{\max}$ is 1.7 $\mathrm{m}^2/\mathrm{m}^2$ under natural water conditions without complementing groundwater in the northeast of the Ulan Buh Desert. This observation is likely to be true for the same soil in the underlying surface of the wandering dune, the semifixed dune, and the fixed dune.

The wandering dune and the semifixed dune have the same features of climate, soil type, species composition, and dominant species of the vegetation. Several characteristics of the water balance are similar, for example, the soil water deficit values (W_D) are approximately 0 in the natural vegetation in each of our years of research (Fig. 4), and soil evaporation is greater than transpiration. Moreover, there are clear differences, showing that the proportion of soil evaporation in precipitation in the wandering dune is greater than that in the semifixed dune, whereas cover and LAI are decidedly smaller. It indicates that water resources in wandering dune have not been fully utilized by the vegetation under natural conditions and that the existing water conditions could satisfy the vegetation developing from the wandering dune to the semifixed dune and then further along to the fixed dune, given suitable conditions, that is, the existing vegetation does not attain the soil water carrying capacity of the vegetation in the wandering dune. This vegetation has the potential to extend the leaf index and coverage so that vegetation rehabilitation is feasible on the wandering dune. In practice, to control the transpiration consumption and strengthen the ecological functions of the vegetation in its protection against the wind and in preventing sand from drifting into the composition, the LAI and the coverage of the vegetation should be adjusted to satisfy the water demand for natural plant growth. In other words, they can be controlled in the soil water carrying capacity of the vegetation.

The critical water value in the model is the main factor to affect the soil water deficit value (W_D), which is the basis of studying the soil water carrying capacity of vegetation and is also affected by the weather, soil, other environmental conditions, and the characteristics of the vegetation. Because the adaptability of species to soil water varies, this critical soil water value is different. Therefore, how to ascertain and use this critical soil water value to reflect water requirements for assuring normal plant growth more exactly will be studied further.

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