植物生态学报 1997， **21** (3)208～225
*Acta Phytoecologica Sinica*

# 依据野外实测的蒸腾速率对几种沙地灌木水分平衡的初步研究

董学军 张新时 杨宝珍

（中国科学院植物研究所，北京 100093）

**摘要** 本文旨在将毛乌素沙地植被建设的水分平衡与半固定沙丘持续发展原则应用于治沙造林的实践中。毛乌素沙地是一个灌木“王国”，然而沙地灌丛植被的发育常常受到水分亏缺的严重制约。为此，根据水分平衡的原则与方法确立适宜的植物种植密度，对沙地植被的经营管理具有重要的指导意义。在水分平衡研究中，蒸散是最难估计的一项。本文提供了一种根据叶面积指数的季节变化与蒸腾速率的观测资料计算蒸腾耗水量的方法，并根据沙地水分平衡的要求估算了几种优势灌木的适宜种植密度。结果表明，毛乌素沙地灌丛生态系统的蒸发散主要来自植物蒸腾作用；在所研究的植物当中，除沙地柏（*Sabina vulgaris*）可以形成很大的密度外（因其强的蒸腾控制能力），其它灌木的适宜种植密度应控制在使沙丘处于半固定状态的水平上。

**关键词** 毛乌素沙地 灌木 蒸腾作用 水分平衡 治沙 种植密度

# A PRELIMINARY STUDY ON THE WATER BALANCE FOR SOME SANDLAND SHRUBS BASED ON TRANSPIRATION MEASUREMENTS IN FIELD CONDITIONS

Dong Xuejun, Zhang Xinshi and Yang Baozhen

(*Institute of Botany, Chinese Academy of Sciences, Beijing* 100093)

**Abstract** This paper aims at applying the principles of water balance and the semi-fixed dunes for the establishment of the product-protective systems in Maowusu Sandland (Zhang Xinshi, 1994; 1996) to the practices of afforestation and control of desertification. As water serves as a limiting factor for the shrubs ecosystems in China's Maowusu Sandland, one of the shrubs 'kingdoms' in the temperate arid zones of the world, it is very important to estimate the appropriate planting densities with the aid of the principles and methodologies of water balance for the rational management and sustainable development for the area's vegetation. In this, evapo-transpiration (ET) is the most difficult to be determined accurately. This paper proposes a method for the estimation of seasonal transpiration water loss based on field measured data of transpiration rate, con-

---

本文于1996-10-09收稿，1997-01-06收到修改稿。

This paper is supported by National Science Foundation of China, and is part of the doctorate of the first author.

We thank Dr. Guoke, Mr. Liu zhimao, Mr. Alatengbao and Mr. Zhao Yuxing for helping conduct field measurement of transpiration.

sidering the typical pattern of change of above-ground green biomass during the typical growing seasons from mid-April to mid-October. The evaporation from sand surface during the growing seasons is estimated by using a semi-empirical model and taking the monthly mean temperatures at sand surface as the input. Finally, the appropriate planting densities for the major shrubs are discussed as constrained by the water balance equation. According to the results obtained, the evapo-transpiration of the shrubs ecosystems of Maowusu Sandland comes mainly from plants rather than the soil. As a result, the appropriate planting densities for the dominant shrubs ought to be controlled at such a level that the dunes are semi-fixed by the plants, with the exception of *Sabina vulgaris* stands having a high density owing to its powerful capability of transpiration control.

**Key words** Maowusu Sandland, Shrubs, Transpiration, Water balance, Control of desertification, Planting density

The ecological problems of the Maowusu Sandland have received tremendous recognition from the world-wide academic circles in the past decades (Petrov, 1966; 1967; Department of Geography of Beijing University, 1983; Dong Guangrong *et al.*, 1988). It is only in recent years, however, that a set of comprehensive principles on the rational management for the shrubs-dominated sandland vegetation has been proposed with an appropriate ecological lucidity (Zhang Xinshi, 1994; 1996), in which the most crucial ones are the principles of water balance and the semi—fixed dunes which emphasize that the appropriate dune vegetation coverage in this area, considering water and heat balance, ought to be near such a level that the dunes are semi-fixed by plants. This hypothesis, satisfying the frequently occurred intuition of many ecological workers, is established quantitatively, however, based on the overall vegetation-climate relations in this area (Zhang Xinshi, 1994; 1996). In order for this research result to be used in the practices of afforestation and desertification control, some small scale research efforts are required to estimate the suitable planting densities for the specific shrubs vegetation in light of water balance. This can be best fulfilled by assuming an observation oriented approach, which relies heavily on the field measured data of transpiration for the major shrubs species in this area.

There are two considerations in assuming this approach. First, in all the terms in the water balance equation, evapo-transpiration (ET) has long been regarded as the most difficult one to determine accurately (Monteith, 1975; Shuttleworth & Wallace, 1985; Shuttleworth, 1993). The reason for this lies not only in the fact that the appropriate micro-meteorological observations, especially the ones describing both the vertical and horizontal variations of the parameters are, at present, mainly lacking at local sites, but also in the reality that evapo-transpiration itself has long been a complicated process. So, the application of the approaches based on the well-known 'surface resistance' paradigm, proposed by Penman and improved by others (Monteith, 1975; Shuttleworth & Wallace, 1985; Shuttleworth, 1993), is difficult in a complicated ecological situation, such as the one in the dune-dominated Maowusu Sandland, when sufficient profile-observations are lacking. Fortunately, the direct leaf-level measurement of transpiration has been made rather easy with the widespread use of porometric method and it is indeed a shortcut to estimate directly the transpiration water loss if the canopies under consideration are sparse in character. Then, secondly, why does the sparsity of the typical shrubs canopies make it feasible for this approach, i. e. , using the field measured data of transpiration rate in the estimation of the ET, to be used. Because the light relations of different leaves within the typical shrubs canopies are relatively similar with one another compared with those of the typical broad-leaved canopies. When both the direct sunlight, penetrating through the relatively wider spacing among the tiny leaves' and reflected sunlight from the sand surface come to reach the leaf surfaces, the change in transpiration rate within the canopies may be relatively smaller than that for the typical broad-leaved canopies. This will advocate the use of leave-level measurements to estimate transpiration from plant stands.

In China, there have been fruitful research conducted at similar situations and focused also on the study of transpiration from some psammophytes (Liu Yingxin, 1963; Huang Yinxiao and Lin Shunhua, 1974; Liao Rutang and Zhang Wenjun, 1992). However, it is surprising that the calculated transpiration from sandland plant stands exceeded the available rainfall input significantly (Liu Yingxin, 1963). This situation may partly be caused by using the peak green biomass as a mean value for the biomass contributing to transpiration during the whole growing period. In addition, the transpiration measurement itself for similar plants and in similar areas, as reported by different workers, have been shown to differ considerably (Liu Yingxin, 1963; Liao Rutang and Zhang Wenjun, 1992; Dong Xuejun *et al.*, 1994; Yang Baozhen *et al.*, 1994; Guo Ke *et al.*, 1996). As a result, more accurate measurement of transpiration and a better estimation of transpiration water loss from plant stands are to be made in order for the assessment of water balance to be more rational in Maowusu Sandland. In this paper, we first propose a method for the estimation of the seasonal transpiration water loss based on field measured data of transpiration rate, considering the typical pattern of change of above-ground green biomass during the typical growing seasons from mid-April to mid-October. The evaporation from sand surface during the growing seasons is estimated by using a semi-empirical model and taking the monthly mean temperatures at sand surface as input. Finally, the appropriate planting densities for the major shrubs are discussed as constrained by the water balance equation.

## 1 MATERIALS AND METHODS

### 1.1 Research site and its scientific importance

All the measurements were carried out at the typical substrates, i. e. , the aeolian sand dunes accumulated on the Cretaceous and Jurassic rocks, in Yi Jin Huo Luo Banner and Wu

Shen Banner, Yi ke Zhao League, Inner-mongolia, the typical area of Maowusu Sandland, during the period from 1989 to 1992. The prevailing climate here is of the temperate grassland type. However, owing to the extensive covering of sand and remarkable influences by landscape heterogeneity, the substrates here are diversified greatly, creating the highly varied micro-habitats (Chen Zhongxin and Xie Haisheng, 1994) suitable for the survival of a wide spectrum of plant and animal species, among which the sandy shrubs species are of highly ecological and economic importance. The research site locates at the southeastern part of the Ordos ecotone, where the potential responses of the natural ecosystems to climate changes have been considered to be very sensitive (Zhang Xinshi, 1994), and consequently, an understanding of the characteristics of water flux in the sand-shrubs system will be helpful to uncover the response patterns of this area's natural vegetation to possible climate changes. In forestry practices, the accurate estimation of transpiration water flux from natural vegetation can be helpful in the design of optimal planting densities for the artificial and semi-artificial vegetation.

**1.2** Water balance of the sand dune

The water balance equation for a typical soil layer can be written as

$$P = R + D + E + T + W_2 \tag{1}$$

in which $P$ is precipitation, $R$ is surface runoff, $D$ is deep layer seepage, $T$ transpiration water loss, $E$ is evaporation from soil surface and $W_2$ is the storage term by soil layers. $W_2$ can be negligible if the time period considered is longer than one month (Hillel, 1980). In Maowusu Sandland, the surface runoff occurs almost always at soft and hard ridges, for it is unlikely to have significant runoff on typical dunes (Yang Baozhen *et al.*, 1994). As a result, Eq. (1) can be reduced to

$$T = P - D - E \tag{2}$$

by which the transpiration water loss (consumption) by plants could be obtained.

**1.3** Estimation of evaporation from sand surface

Although it has been widely recognized that the sandy soils can powerfully limit the surface evaporation when soils are sufficiently dry (Davis, 1974; Hillel, 1980), it is not at all redundant to pay the surface evaporation a specific consideration in the research of water balance. We adopt the method developed by Kobayashi Tetsuo (Kobayashi Tetsuo, *et al.*, 1992) for calculating the water vapor flux in the dry sand layer:

$$q = 0.0629\alpha \exp(0.0629T_0 - 36.92)\{f(\theta_\delta) - f(\theta_0)\}/\{1 - \exp(-0.0629\alpha\delta)\} \tag{3}$$

in which

$$f(\theta) = (1/9)\theta^9 - (18.9/8)\theta^8 + 21.40\theta^7 - 105.18\theta^6 + 299.14\theta^5 - 472.64\theta^4 + 311.90\theta^3$$

$q$ is evaporation rate (cm/s), $\alpha$ is the rate of change in temperature with the change of soil depth, $T_0$ is the temperature at sand surface, $f(\theta)$ is a function of soil wetness, $\theta_\delta$ is the volumetric water content at the interface between the wet and dry layer, $\theta_0$ is the surface water content of the sands, and $\delta$ is the depth of the dry surface layer (cm). If $\theta_\delta$ assumes a value of

2%~2.5%, then $f(\theta_\delta)$ can be approximated to $f(\theta_\delta)=130$; and when the temperature change within the dry surface layer is far less then 16k, i.e., $\alpha\delta << 16k$, Eq. (2) can be reduced to

$$q = \exp(0.0629T_0 - 36.92)(130 - f(\theta_0))/\delta \quad (4)$$

We use Eq. (4) to calculate the evaporation from sand surface, because both conditions, $\theta_\delta=$ 2%~2.5% and $\alpha\delta << 16k$, can generally be satisfied at the typical climatic conditions in Maowusu Sandland (Kobayashi Tetsuo, *et al.*, 1992).

**1.4** Measurement of transpirtion rate for individual leaves or leafy twigs

All the measurements of transpiration were made in field condition on some frequently occured plants, especially shrubs, in this area, by a mechanic balance (LI Bo, *et al.*, 1964; Guo Ke, *et al.*, 1996), a LI-1600 Steady State porometer (Shulze, *et al.*, 1980) and a LI-6000 photosynthesis Analyzing System (Zheng Hailei, *et al.*, 1992), respectively. On each day of measurement, data were collected every two hours from 8 to 20 o'clock for the top, middle and lower layers of the canopies, with 5~10 replications for each layer. In order to keep a direct comparison with other worker's results, the unit used for Li-Cor instruments is

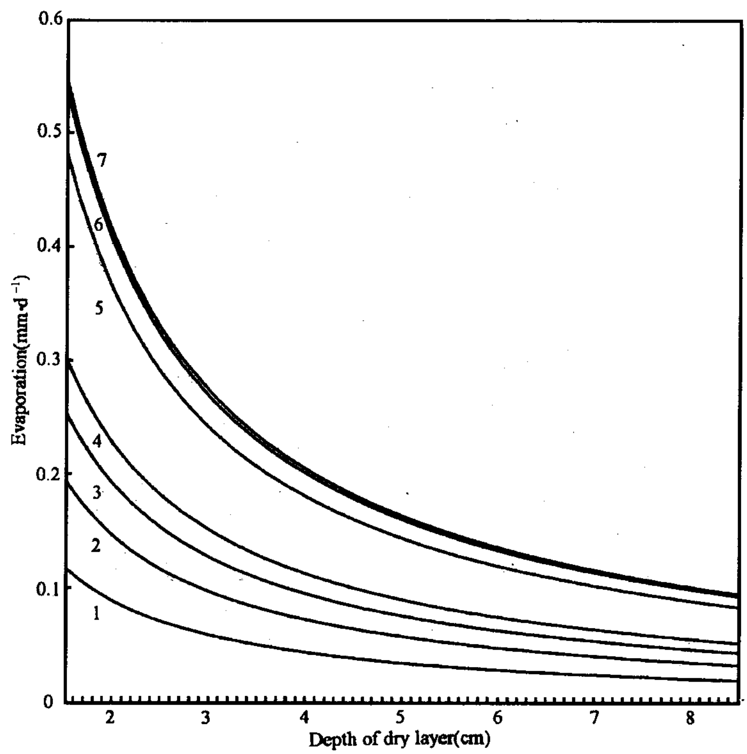


Fig. 1 Dependence of evaporation from the dune surface on the depth of the dry surface layer, calculated with the monthly means of the dune surface temperature in Maowusu Sandland from April to October in 1991. Each curve is labelled with a number from 1 to 7, which stands for October, April, September, May, June, July and August, respectively
1. Oct. 2. April 3. Sep. 4. May 5. June 6. July 7. Aug.

in $\mu g \cdot cm^{-1} \cdot s^{-1}$, whereas that for quick-weighting method is in $mg \cdot g^{-1} \cdot min^{-1}$ (see table 2 for details). If the transpiring period for each day is set to 12 hours, and the actual leaf area indices (measured as the maximum of shadowed leaf area) are considered, then, daily transpiration water consumption (DTWC), $T(L,t)$, for the LI-cor instruments, can be expressed as

$$T(L,t) = 36 \times 10^{-3} \times L \times \sum_{i=1}^{n}(s_i \triangle t_i) \tag{5}$$

where $T(L,t)$ is for DTWC (mm day$^{-1}$), $L$ is leaf area index ($m^2/m^2$), $s_i$, the mean of transpirtion rate of the $i$th measurement ($\mu g \cdot cm^{-1} \cdot s^{-1}$), $n$, the number of measurement for the whole day, $\triangle t_i$ is the time interval between measurements (hr). Daily transpiration water consumption by unit LAI can be expressed as $T(t)=T(L,t)/L$.

For the quick-weighting method, DTWC, $T(L,t)$ is

$$T(L,t) = 60 \times 10^{-6} \times L \times \sum_{i=1}^{n}(\alpha s_i \triangle t_i) \tag{6}$$

where $T(L,t)$ is DTWC ($mm \cdot d^{-1}$), $\alpha$ is the leaf area of the unit leaf fresh weight, and $s_i$ is the mean of transpiration rate of the $i$th measurement ($mg \cdot g^{-1} \cdot min^{-1}$). Other symbols are the same as in Eq. (5).

**1.5** Estimation of LAI for the shrubs stands

Within typical stands of *Artemisia ordosica* at soft ridge, *A. ordosica* at dune and *Caragana intermedia* at dune, ten healthy twigs for each stand were selected, and the changes of their lengths, from July to September were measured in 15-day intervals. The lengths of the twigs can be related to corresponding leaf area (Dong Xuejun, *et al.*, 1993). By relating the averaged twig length for the early Sep. with the biomass data of the same period, we obtain the leaf area index (LAI) for this time (early Sep.), which is presumably considered as the maximum of the green biomass of the growing season. The LAI's for other periods are obtained by extrapolating from the observed data, with the assumption that the accumulation of green biomass begins from April 15. So the change in LAI with time (day) is shown in Fig. 2.

**1.6** Estimation of transpiration water consumption by plants during the growing seasons

The transpiration water consumption by plants during a time interval from $t_0$ to $t_1$ can be expressed as

$$T = \int_{t_0}^{t_1} T(t)L(t)dt \tag{7}$$

in which $T(t)$ stands for daily transpiration water consumption by unit LAI at time $t$ (day) ($mm \cdot day^{-1}$), and $L(t)$ represents the LAI at time $t$ (day).

The pattern of change of $T(t)$ during the growing season may be very complicated (Liu Yingxin, 1963), however, the following treatment, we believe, can be tolerable: $T(t)$ first remains at a constant value, $T_0$, averaged through the total measurements during the period from April 15 to Sep. 1; then it goes down linearly until reaching zero on Oct. 15, i. e.

$$\begin{cases} T(t) = T_0 & 0 \leqslant t \leqslant 135 \\ T(t) = at + b & 135 \leqslant t \leqslant 180 \\ T(t) = 0 & t = 180 \end{cases} \quad (8)$$

Let $L(t)$ change according to the trends in Fig. 2 from April 15 to Sep. 1, and then keep constant till Oct. 15, i. e.

$$\begin{cases} L(t) = L(t) & 0 \leqslant t \leqslant 135 \\ L(t) = L_0 & 135 \leqslant t \leqslant 180 \end{cases} \quad (9)$$

Now, the transpiration water consumption by plants during the growing season can be expressed as

$$T = T_0 \int_0^{135} L(t)dt + L_0 \int_{136}^{180} T(t)dt \quad (10)$$

## 2. RESULTS AND DISCUSSIONS

### 2.1 Evaporation from the dune surface

**Table 1 Comparison of evaporation water losses from sand dune surface under different climatic conditions in Maowusu Sandland in 1990**

| Time of measurement | Surface temperature (℃) | Volumetric water content (%) | Depth of dry layer (cm) | Evaporation rate ($mm \cdot h^{-1}$) |
|---|---|---|---|---|
| Aug. 2 (Clear) | | | | |
| 9:30 | 23.1 | 0.054 | 0 | — |
| 11:30 | 37.6 | 0.013 | 0.7 | 0.1887 |
| 13:30 | 43.4 | 0.010 | 1.1 | 0.1729 |
| 15:30 | 42.0 | 0.004 | 0.7 | 0.2488 |
| 17:30 | 35.0 | 0.004 | 0.9 | 0.1246 |
| 19:30 | 28.7 | 0.005 | 0.9 | 0.0838 |
| Total | | | | 1.6376 $mm \cdot d^{-1}$ |
| Aug. 17 (Cloudy) | | | | |
| 8:00 | 22.3 | 0.004 | 5.5 | 0.0092 |
| 10:00 | 26.3 | 0.004 | 5.8 | 0.0112 |
| 12:00 | 33.3 | 0.003 | 5.9 | 0.0171 |
| 14:00 | 31.7 | 0.003 | 5.9 | 0.0154 |
| 16:00 | 24.4 | 0.004 | 5.9 | 0.0098 |
| 18:00 | 25.2 | 0.003 | 5.9 | 0.0103 |
| 20:00 | 19.3 | 0.007 | 5.8 | 0.0072 |
| Total | | | | 0.1604 $mm \cdot d^{-1}$ |

The sand surface temperature, its wetness and the dry-layer depth were measured on a typical clear day after rainfall (Aug. 2, 1990), and a typical cloudy day (Aug. 17, 1990), respectively, in order to estimate the evaporation rates at the different time of a day (mm/hr) and the daily evaporation (mm/day) (see Table 1 for details). It can be seen that, on the clear day just after a rainfall (Aug. 2), the evaporation rate was so high that it almost reached the level of plant transpiration rate (see Table 2). However, on the cloudy day (Aug. 17), when a deeper dry surface layer developed, the evaporation rate was very low, being one tenth, approximately, of the values of Aug. 2. The surface evaporation might not be high due to the barrier formed by the dry surface layer. Next, we will estimate the evaporation water loss during the growing season, i. e. , from April to October, of 1991. Substituting the mean values of the dune surface temperature (Wang Jiaxiang, 1992) from April to October 1991 to Eq. (4), and assuming that the volumetric water content of the surface soil is constantly set to 0. 4%, the change in soil evaporation with the depth of dry surface layer is obtained as shown in Fig 1. Soil evaporation changed with both the depth of dry surface layer and the time (owing to the difference in temperature for different months). The values for April and October, when the low temperatures prevailed, were lower than those for June, July and August when the mean temperature was higher. In addition, the soil evaporation dropped sharply when the dry surface layer increased. According to the previous works in similar soils

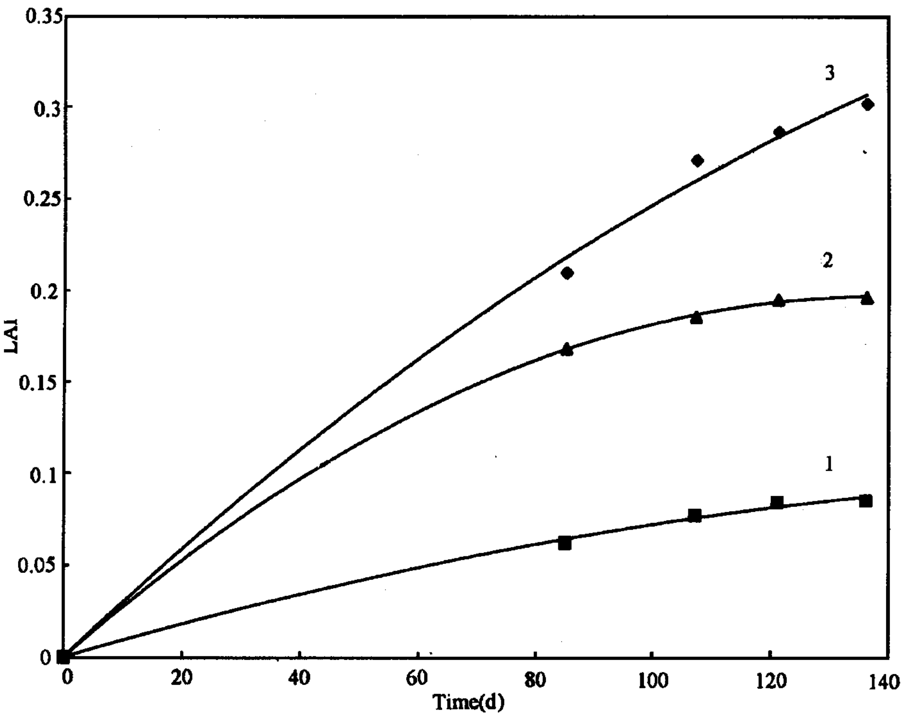


Fig. 2　Changes of leaf area index of *C. intermedia* and *A. ordosica* during the growing period of 1991, based on the measured values of the growth rates of young twigs from July 10 to September 10 of the year, and with the assumption that the augment of LAI begins from April 15. *A. ordosica* growing at the soft ridge (Plot I) is represented by Line 1, *C. intermedia* is represented by Line 2 and *A. ordosica*, growing at the soft ridge with a deep layer sand cover (Plot II), is represented by Line 3. The fitted equations for the augmentation of the LAI's
are $Y=-2\times10^{-6}X^2+0.001X$ (Line 1), $Y=-1\times10^{-5}X^2+0.0029X$ (Line 2)
and $Y=-6\times10^{-6}X^2+0.0031X$ (Line 3)

(Jiang Ailiang, 1963; Chen Wenrui and Zhang Jixian, 1963 ; Kobayashi Tetsuo *et al.*, 1992). we assume a mean value for the depth of dry surface layer as 3.5 cm, and estimate, by Eq. (4), that the soil evaporation in Maowusu Sandland from April to October 1991 was about 32.7mm, which is about 11.01 percent of the rainfall of 296.9mm received during the same time period.

**2.2** Seasonal changes of leaf area indices(LAI's) for some shrubs

As calculating the seasonal transpiration water loss by plant communities using the LAI of the actively growing period might exaggerate the actual values (liu Yingxin, 1963; Liao Rutang and Liao Rutang, 1992), the appropriate estimation of the change in LAI during the growing season becomes important. As a result, we obtained the change in LAI, for two shrub species in Maowusu Sandland, with time(in a ten-day interval from July to September 1991), by measuring the growth rates of young twigs, correlating these growth rates with leaf area equivalencies and also considering other information of field survey, as shown in Fig. 2. The increase in LAI is assumed to begin from April 15, and arrive at a maximum level on September 1, after 135 days' growth. The trends of the changes in LAI's from April 15 to July 10 are obtained by the extrapolation of the observed data. It can be seen that the LAI of *A. ordosica*, growing at the sand covered soft ridge, was higher than that growing at the soft ridge. This difference might not be caused by the difference in plant density, but by the difference in the ratio of dried twigs between the two stands.

**2.3** Variations of the daily transpiration of some sandy shrubs

Table 2 summaries the results of transpiration measurements from 1989 to 1992 on some sandy shrubs in Maowusu Sandland. Some of the transpiration results measured with Li-1600 porometer have been re-calculated with some corrections(esp. in leaf area)and are different from the previously reported ones (Dong Xuejun, *et al.*, 1994; Yang Baozhen, *et al.*, 1994). The results are converted into the precipitation equivalents(in millimeters of water, mm)in order to calculate water balance conveniently. The column 'Daily transpiration' stands for the amount of water transpired by different plants in their actual densities. It can be seen that the typical value of the DT's(Daily transpiration)for the dune-grown shrubs ranges from about 1 to 2 mm/day. Ground water is usually unavailable to these shrubs. However, for the species accessible to water table, such as *S. Psammophylla* and *S. vulgaris* growing at the dune depressions, the DT's can be up to or even more than 5 mm/day. Based on the most frequently occurred LAI values of different plants, the possible daily transpiration by unit LAI(PDTUL) for different species and on different days, is also calculated. This (PDTUL) is virtually an alternative of the expression of transpiration rate. (1) The PDTU's differ between plants having different ecological features. The PDTUL for *S. Psammophylla* and *A Sphaerocephala* is higher than the others. This may be the result of the relatively ample water supply to these two plants(the former's root systems can reach the ground water table and the latter favors from its sparsity in community structure). How-

**Table 2 Estimated values of daily transpiration water loss, calculated as the accumulations of transpiration(μg · cm$^{-2}$ · s$^{-1}$), for some shrub species in Maowusu Sandland**

| Plant species | Site | Time | LAI | Transpiration rate (μg · cm$^{-2}$ · s$^{-1}$*, mg · g$^{-1}$ · min$^{-1}$**) | Daily transpiration (mm · d$^{-1}$) | Possible daily transpiration by unit LAI (mm · d$^{-1}$) | Weather or PPFD (μEm$^{-2}$ · s$^{-1}$) | Air temperature (℃) | Soil water content(%) |
|---|---|---|---|---|---|---|---|---|---|
| *A. ordosica* | Dune | 1989-09-19 | 0.30 | 3.63±0.54** | 1.77 | 5.84 | 519±193 | 16.58±2.07 | 3.5±0.4 |
| | Dune | 1990-07-05 | 0.12 | 13.08±1.07*** | 0.74 | 6.41 | 1798±151 | 27.61±1.70 | 2.9±0.3 |
| | Dune | 1990-07-05 | 0.30 | 13.72±0.94*** | 2.02 | 6.66 | 1874±175 | 27.76±1.58 | 1.8±0.1 |
| | Dune | 1991-08-16 | | 15.54±0.74* | 2.04 | 6.71 | 914.9±97.9 | 28.99±0.60 | 2.9±0.3 |
| | Dune | 1991-09-01 | | 18.96±0.91* | 2.49 | 8.19 | 887.6±82.9 | 26.55±0.58 | 3.2±0.4 |
| | Dune | 1992-06-25 | | 12.61±1.18* | 1.66 | 5.45 | 328.2±63.0 | 22.37±0.71 | 2.1±0.2 |
| | Dune | 1992-08-15 | | 16.45±0.65* | 2.16 | 7.11 | 1074±101 | 25.07±0.45 | 4.9±0.3 |
| *C. intermedia* | Dune | 1991-06-23 | 0.20 | 12.43±0.87** | 1.25 | 6.30 | Cloudy | — | 12.5±2.3 |
| | Dune | 1991-08-21 | | 11.74±0.60* | 1.01 | 5.07 | 1067±78 | 29.93±0.42 | 10.7±1.8 |
| | Dune | 1991-09-06 | | 12.30±0.44* | 1.05 | 5.31 | 1218±85 | 26.74±0.57 | 10.1±1.8 |
| | Dune | 1992-06-28 | | 6.64±0.68* | 0.57 | 2.89 | 766.0±84.9 | 23.38±0.51 | 6.7±1.7 |
| | Dune | 1992-08-15 | | 9.48±0.63* | 0.81 | 4.10 | 1491±89 | 25.35±0.43 | 9.6±1.4 |
| *A. sphaerocephala* | Dune | 1989-08-19 | 0.10 | 6.21±0.77** | 0.89 | 9.26 | Clear | — | 2.2±0.4 |
| | Dune | 1989-08-20 | | 5.63±1.18** | 0.80 | 8.46 | Clear | — | — |
| | Dune | 1989-08-21 | | 7.74±1.44** | 0.95 | 9.98 | Clear | — | — |
| | Dune | 1989-09-19 | | 2.66±0.61** | 0.38 | 4.03 | 519±193 | 16.58±2.07 | 3.5±1.3 |

续表 Table 2

| Plant species | Site | Time | LAI | Transpiration rate ($\mu g \cdot cm^{-2} \cdot s^{-1}$* $mg \cdot g^{-1} \cdot min^{-1}$**) | Daily transpiration ($mm \cdot d^{-1}$) | Possible daily transpiration by unit LAI ($mm \cdot d^{-1}$) | Weather or PPFD ($\mu Em^{-2} \cdot s^{-1}$) | Air temperature (℃) | Soil water content (%) |
|---|---|---|---|---|---|---|---|---|---|
| *S. Psammophylla* | Lowland | 1991-06-23 | 0.47 | 6.93±0.50** | 4.52 | 9.62 | Cloudy | — | — |
| | with | 1991-08-18 | | 18.59±1.06* | 3.77 | 8.03 | 889.6±70.4 | 30.30±0.32 | 8.6±1.8 |
| | | 1991-09-05 | | 20.50±1.18* | 4.09 | 8.20 | 661.2±60.2 | 24.97±0.41 | 10.1±1.8 |
| | sand | 1991-09-17 | | 15.65±0.76* | 3.23 | 6.88 | 792.5±81.6 | 21.33±0.30 | 6.8±1.8 |
| | | 1992-06-29 | | 8.65±0.36* | 1.75 | 3.72 | 973.8±49.9 | 26.94±0.19 | 6.7±1.7 |
| | cover | 1992-08-11 | | 24.42±1.16* | 5.06 | 10.8 | 931.5±47.6 | 27.86±0.27 | 12.0±2.0 |
| | | 1992-09-26 | | 1.36±0.09* | 0.28 | 0.59 | 794.0±92.1 | 17.75±0.47 | 11.8±2.2 |
| *H. mongolicum* | Dune | 1989-08-19 | 0.40 | 7.67±1.60** | 1.97 | 4.92 | Clear | — | 2.2±0.4 |
| | Dune | 1989-08-20 | | 6.49±1.05** | 1.50 | 3.75 | Clear | — | — |
| | Dune | 1989-08-21 | | 8.62±1.30** | 1.99 | 4.98 | Clear | — | — |
| *S. vulgaris* | Top dune | 1991-09-08 | 3.96 | 1.48±0.15* | 2.53 | 0.64 | 1326±112 | 27.15±1.08 | 1.8±0.2 |
| | Depression | 1991-09-08 | 5.69 | 2.14±0.14* | 5.42 | 0.95 | 1268±102 | 26.29±0.98 | 3.3±0.2 |
| *C. komarovii* | Lowland | 1989-09-19 | 0.79 | 6.59±1.03** | 2.31 | 2.91 | — | — | — |
| | Dune | 1990-07-05 | 0.79 | 7.50±0.84*** | 2.92 | 3.68 | 2096±196 | 27.62±1.67 | 2.5±0.2 |
| | Dune | 1990-07-05 | 0.12 | 9.94±1.18*** | 0.58 | 4.66 | 1655±299 | 27.33±1.86 | 2.9±0.3 |

* measured with LI-1600 Portable Steady State Porometer ** measured with quick-weighing method *** measured with LI-6000 Portable Photosynthesis System (in $\mu g \cdot cm^{-2} \cdot s^{-1}$)

ever, for the two clonal shrubs, *H. Mongolicum* and *S. Vulgaris*, having a higher density and more intensive water competition between individuals, the PDTUL tends to be lower. (2) The PDTUL also shows a tendency of change in relation to phenology. This can be seen in the lowest observation of *S. Psammophylla* on Sep. 26 when the mean temperature of daytime dropped to 17.75℃. (3) Transpiration rate has also some dependence on the environmental factors, such as soil moisture condition, air temperature, humidity and photosynthetic photon flux density (PPFD), etc. However. according to the field measurement, its dependence on soil moisture seems more conspicuous. The humidity data hasn't been included in Table 2 because the absolute value of humidity monitored in our LI-1600 porometer has some departure from the standard psychrometer data.

**2.4** Seasonal water consumption by some sandy shrubs

It can be calculated from Table 2 that, for *Artemisia ordosica* and *Caragana intermedia*, $T_0$ is 6.623mm $day^{-1}$ and 4.732 mm $day^{-1}$, respectively; their $L_0$'s are 0.304 (Plot II), 0.075 (Plot I) and 0.1985 (*C. intermedia*). Having the values of $T_0$'s, $a$ and $b$ can be obtained by Eq. (8). For *A. ordosica*, $a=-0.151$ and $b=27.094$; for *C. intetmedia*, $a=-0.108$ and $b=19.358$. With the fitted polynomial functions in Fig. 2 and other related numbers substituted into Eq. (10), the transpiration water consumption by *A. ordosica* and *C. intetmedia* stands from April 15 to October 15, 1991, can be calculated. The results are 197.79mm for *A. ordosica* at Plot II, 60.16mm for *A. ordosica* at Plot I and 106.28mm for *C. intermedia*, respectively. Assuming that the changes in LAI during the growing seasons for some other psammophytes are the same as that for *C. intermedia*, their transpiration water loss can also be estimated as the above method (see Table 3).

**Table 3 Seasonal water consumption of some sandy shrubs in Maowusu Sandland from April 15 to October 15 in 1991. The average values of the PDTUL for different plants in Table 2 are used as the mean transpiration rates in the calculation of transpiration water consumption (mm $day^{-1}$, unit LAI) But the data of *S. psammophylla* on Sep. 26 is not included.**

| Name of plant | LAI | Transpiration water consumption (mm) |
|---|---|---|
| *Artemisia ordosica* | 0.112～0.304 | 74.8～197.79 |
| *Caragana intermedia* | 0.1978 | 106.28 |
| *Artemisia sphaerocephala* | 0.0953 | 136.09 |
| *Salix psammophyla* | 0.47 | 416.90 |
| *Hedysarum mongolicum* | 0.40 | 206.06 |
| *Sabina vulgaris* | 3.96 (top dune) | 356.83 |
| | 5.69 (depression) | 512.73 |
| *Cynanchum komarovii* | 0.124～0.79 | 53.63～335.33 |

**2.5** Water balance in the sandland and the appropriate planting densities for some major shrubs

Because the *LAI*'s shown in Table 3 are the typical values in the actively growing period, the corresponding values for transpiration water consumption should also be typical. It can be seen that, for. *A. ordosica* and *Cynanchum komarovii*, transpiration water consumption changed significantly with density, sometimes exceeding the amount of rainfall water in the same period(296.97mm). So, it may be difficult to keep a balanced water regime in the communities (for example for *Cynanchum komarovii* when LAI = 0.79) if the ground water is unavailable for plants; in addition, the fact that, the transpiration of *Sabina vulgaris* growing at top dune well exceeded the rainfall supply, implies that this stand(of *S. vulgaris*) might suffer from water deficit(unpublished data). We suppose that *S. vulgaris* growing healthily at the lowland(with a thin layer of sand cover) and *Salix psammophylla* growing at the foot or dune may rely heavily on the down-flowing or laterally-coming water from the surrounding dunes, although it might be difficult to be detected directly in field conditions.

**Table 4 Water content for different soil layers in *Hedysarum mongolicum* community measured in the Summer of 1989. Also shown are the corresponding values for the bare dune**

| Date | Depth(cm) / Profile | 0~5 | 10~20 | 30~40 | 50~60 | 70~80 | 90~100 | 110~120 | |
|---|---|---|---|---|---|---|---|---|---|
| July 20 | Community | 3.90 | 4.18 | 6.29 | | | | | |
| | Bare dune | 4.00 | 6.29 | 6.05 | 3.75 | 3.04 | 3.33 | | |
| July 22 | Community | 5.63 | 5.50 | 6.79 | 8.86 | 6.78 | 0.02 | | |
| | Bare dune | 4.41 | 6.29 | 7.82 | 7.48 | 1.98 | 5.82 | 2.60 | 3.10 |
| July 24 | Community | 4.27 | 5.84 | 5.69 | 6.66 | 8.01 | 8.17 | 0.75 | 1.72 |
| | Bare dune | 2.17 | 4.69 | 4.40 | 7.06 | 8.24 | 6.94 | 7.03 | 7.12 |
| Aug. 6 | Community | 5.84 | 3.36 | 4.15 | 4.48 | 4.71 | 5.80 | 5.65 | 4.75 |
| | Bare dune | 5.70 | 3.57 | 4.25 | 3.93 | 3.32 | 3.76 | 3.51 | 3.47 |
| Aug. 15 | Community | 2.37 | 2.51 | 2.08 | 2.56 | 2.59 | 2.98 | | |
| | Bare dune | 2.94 | 3.53 | 2.58 | 3.04 | 2.52 | 5.06 | | |
| Aug. 27 | Community | 2.98 | 4.30 | 3.51 | 2.21 | 2.41 | 2.66 | | |
| | Bare dune | 4.12 | 5.32 | 4.89 | 5.35 | 6.58 | 5.80 | | |
| Aug. 17 | Community | 1.18 | 1.98 | 1.29 | 2.55 | 3.24 | 3.06 | | |
| | Bare dune | | | | | | | | |
| Sep. 19 | Community | 1.38 | 3.22 | 2.89 | 2.70 | 2.48 | 2.47 | | |
| | Bare dune | 0.67 | 2.98 | 3.28 | 2.57 | 2.44 | 3.57 | | |

Next, we will discuss the role played by deep seepage and condensed water in the water balance of the typical sandland. Since the majority of the particles of the sandy soils is course, deep seepage may generally be remarkable at the bare dunes. However, when the dunes are covered by plants, especially the shrubs with their wide spread of root systems, deep seepage may not be so remarkable. This supposition, based on field experiences (see Table 4), can receive a support, however, from a simple calculation. Supposing the average water content of the soil, covered densely with plants, is 2%, and soil bulk density is $1.64 g/cm^3$, then, the rainfall requirement for a soil profile of 2m depth to reach a saturated water content of 5%~6% can be estimated as $P=(6\%-2\%)\times 1.64\times 2000=131.2mm$; if the saturated water content is set to 5%, $P$ becomes 98mm. Because no occurrence of rainfall in 1991 exceeded 50 mm according the local observations, it is certain that for every occurrence of rainfall, all the water could be held within the root zone and the deep seepage be avoided. However, there have been some different opinions as to whether the condensed water plays a significant role in the water balance in the arid area. Liu Yingxin (1963) conjectured that the huge consumption of water by some psammophytes might partly come from the condensation of water in the sandlands. Hillel (1982) and Evenari *et al.*, (1982) believed, however, that the condensed water could be negligible in the water balance of Negev Desert. According to our measurement on August 5, 1990, the dew water on the leaves of *C. intermedia* and *C. komarovii* accounted for 8.22% and 10.54%, respectively, of the leaf fresh weights. For *C. komarovii*, this equals to 0.04mm of water, which can be evaporated in 15 minutes in a typical daytime condition. Another portion of the condensed water forms at the sand surface owing to the occurrence of large temperature variations and the active energy exchange at the dune surface during a day, in particular a clear day. We re-analyzed the data collected by Jiang Ailiang (1963) at the wind-facing slope of the dune at Shajingzi, Minqing of Gansu province. The course of change of soil water content of the top 0～20 cm depths within 35 hours after a rainfall was measured. Water content of the top layer (0～5cm) dropped quickly during 11 hours after the rain (occurred at 8 o'clock Am), but when measured in the early morning of the next day, water content for top 0～2cm and 2～5cm increased from 0.4% to 1%, and 2.3% to 3%, respectively. Accordingly, the accumulation of condensed water was estimated to be equal to a water content of about 0.6%～0.7%. This amount can be summed to reach 0.57mm by integrating in the top 0～5cm depths, and it can be evaporated into the air in 7hr from 8 Am to 3 P.M. in a typical clear day after rain, as indicated in Table 1. With these considerations, we tentatively support the idea that the condensed water plays only a minor role in the water balance of the shrubs at a typical sandland substrate, despite the fact that it might be crucial to some herbaceous and bryophyte species. As a result, we neglect the role of the condensed water in the water balance of sandy shrubs, which will be discussed in the following parts of this section.

According to the earlier discussions, if plants can cover the dune with a maximum of density, the majority of the rain water can then be absorbed by the root systems without downward percolation, i.e., $D$ in Eq. (1) assumes a value of zero. Subtracting the surface evaporation of 32.7mm from the total rainfall of 297.97mm during the period from April to October 1991, the maximum water available for the transpiration of plants is $E=297.97-32.7=265.27$mm, which serves as a basis for the determination of the suitable planting densities for different plants. From Table 3, the annual water consumption by unit $LAI$ by different plants can be obtained (see Table 5), and when compared with the amount of 265.27mm, the suitable leaf area indices ($LAI_S$) can also be obtained. Next, by using the leaf area possessed by the average individual crown, $A_{pc}$, the suitable densities for different plants, $D_s$, are estimated by $D_s=100\times LAI_s/A_{pc}$, as shown in Table 5.

Some ecological implications of Table 5 are given as follows. (1)*Sabina vuagaris* has the highest $LAI_s$(2. 94). which, however, is lower than the actual LAI shown in Table 2. This gives support to the hypothesis that *S. vulgaris* growing at top dune might also suffer from water starvation. It is suggested that *S. vulgaris* growing at top dune be thinned appropriately according to the suitable density given in Table 5. (2) The $LAI_s$ for *Hedysarum mongolicum* is also high, being 0. 51. This suggested that a relatively high density of *H. mongolicum* is applicable without affecting the soil water balance. However, there must be a upper limit of density for this shrubs, with which the plant could survive safely even in drought seasons, because it had been observed (Xu qingyun, 1984)that *H. mongolicum* has a tendency to grow denser and denser owing to the feature of clonal growth, and that there had been some evidence of massive death of *H. mongolicum* because of shortage of water (interview with some local people). (3)The $LAI_s$ for *Artemisia ordosica* is roughly the same as the actual occurring LAI at the semi-fixed dune, indicating that water balance could generally be satisfied in a naturally occurring *A. ordosica* stand. However, it has been noted in practice that the growth condition of *A. ordosica* becomes worse with the further fixing of the dune. This might partly be caused by the change in soil physical characters and its effect on water availability. (4)For *Caragana intermedia*, the $LAI_s$ surpasses the naturally occurring LAI significantly. It' s not clear why *C. intermedia* does not increase its densities to the possible value. However, the ecological advantages of *C. intermedia* seems to be remarkable; it can powerful ly reduce transpiration in conditions of drought (Dong Xuejun *et al.*, 1994); the low water potential of its root, shoot and leaf tissues make it easier to absorb water in a dry soil matrix. The root system of *C. intermedia* can penetrate through the hard ridge where the shortage of water occurs frequently. (5)The $LAI_s$ for *Salix psammophylla* is relatively low. This is related with its high transpiration rate(Dong Xuejun, *et al.*, 1994). At the dune, *S. psammophylla* generally exists in low density but with wide spread of its root system, especially in the shallow sand layers(within 1 meter). *S. psammophylla* is mostly suitable to grow at the foot of the dune where the water conditions are favorable and where there are constant accu-

**Table 5 Estimated values of the suitable densities of some sandy shrubs in Maowusu Sandland, as limited by the availability of water, based on the water balance of the soil-plant system**

| Name of plant | Size of canopy($cm^2$) | Leaf area per cluster, $A_{pc}$ | Possible annual water use by unit LAI(mm $year^{-1}$) | Suitable LAI($LAI_s$) | Suitable coverage (%) | Suitable density, $D_s$ (clusters/$100m^2$) |
|---|---|---|---|---|---|---|
| *H. mongolicum* | 200×200 | 3. 60 | 515. 15 | 0. 51 | 42. 3 | 14. 2 |
| *C. intermedia* | 300×280 | 7. 31 | 535. 40 | 0. 49 | 41. 8 | 6. 7 |
| *A. ordosica* | 104×105 | 0. 80 | 650. 60 | 0. 41 | 41. 0 | 51. 4 |
| *S. psammophylla* | 350×370 | 8. 17 | 887. 03 | 0. 29 | 34. 8 | 3. 6 |
| *A. sphaerocephylla* | 110×105 | 0. 50 | 1427. 10 | 0. 19 | 32. 5 | 37. 7 |
| *S. vulgaris* | 60×65 | 1. 09 | 90. 10 | 2. 94 | 82. 1 | 269. 7 |

mulation of sands carried by the wind. (6)The $LAI_s$ for *Artemisia sphaerocephala* is the minimum of all the plants considered. It is consistent with the low density it has in natural conditions. At the early stage of the succession of dune vegetation, *A. sphaerocephala* frequently occurs. However, with the later invasion of *A. ordosica*, it may be expelled gradually. It must be noted that, just as *A. sphaerocephala*, another pioneering plant *Agriophyllum squarrasum* also has a high transpiration intensity (Liao Rutang and Zhang Wenyun, 1992). This (unrestricted transpiring tendency of these two plants) may be closely related to the ample water supply of the dune in the early stage of succession.

The following three points should be noted for the implicit assumptions and simplifications made in the present paper. First, the actual transpiration rates for different plants may well be different from the ones assumed in Table 2. They may change in response to environmental conditions, such as soil water content, PAR, air temperature and humidity, etc., and plant physiological characters, such as tissue water relations and stomatal conductance, etc. So, the transpiration water loss provided in the present paper is only a preliminary estimation. Secondly, the redistribution of water in soils will further reduce the availability of water for plants, even in the densely vegetated locations. But this has not been discussed in the present paper. Thirdly, the uneven distribution of rainfall in the growing seasons was not considered. In fact, the majority of rainfall occurs in July and August, whereas the rainfall in April and May is relatively rare. During the drought period of spring, there sometimes is no rainfall in 40～50 days. So, the actually suitable coverage of vegetation may be less than the figures shown in Table 5. In soils of hard ridge and soft ridge where the water conductivity is even lower, the suitable vegetation coverage should also be lowered accordingly. On the contrary, the appropriate vegetation coverage at the lowland, where the available water is abundant, should be higher than that at the dune. However, generally speaking, the appropriate planting densities at the typical sandland may range from 30% to 40%, as determined by water balance. If the sandland has a vegetation coverage from about 30% to 40%, we call it semi-fixed, or semi-immobile.

Having the principle of semi-fixed dunes for the establishment of the product-protective systems in the Maowusu Sandland, proposed by Zhang Xinshi (1994), it is urgently required that some specific research on the water balance of the major shrubs species at small scale be carried out. This paper is just such an attempt. The suitable planting densities for the major shrubs species obtained in this research will be helpful for the local people in their efforts of shrub-planting in the sand dunes. Further more, the attempt to apply the results of large scale ecological research to the forestry practices will be constructive in the campaign of desert control and sustainable development in the Maowusu Sandland.

## 3 CONCLUDING REMARKS

This research is essentially an attempt to apply the principles of water balance and the semi-fixed dunes for the establishment of the product-protective systems in the Maowusu Sandland, proposed by Zhang Xinshi(1994;1996), to the practices of afforestation and control of desertification. As water is the main concern of the principles, several important terms in the water balance equation, i. e., rainfall input, transpiration, soil evaporation, condensed water and deep percolation, and their ecological significance, are discussed specifically in order to determine the appropriate planting densities for the major shrubs.

(1) The value of the DT (Daily transpiration) from the natural stands of the dune-grown shrubs varies significantly, from 0. 38 mm/day (*A. sphaerocephala*, on Sep. 19, 1989) to 2. 53mm/day (*S. vulgaris*, on Sep. 8, 1991). But the typical value ranges from about 1 mm/day to 2mm/day. Because ground water is usually unavailable to these shrubs, they are frequently faced with problems of water deficit. However, for the species accessible to water table, such as *S. Psammophylla* and *S. vulgaris* growing at the dune depression, the DT can be up to or even more than 5 mm/day.

(2) The possible daily transpiration by unit LAI (PDTUL) is an alternative of transpiration rate. It varies (a) between plants having different ecological features; (b) in relation to phenology; (c) according to soil moisture availability and other environmental factors.

(3) It is estimated that soil evaporation during the typical growing seasons accounts for about 11% of the total rainfall in the same period, and almost 90% of annual rainfall can be consumed by plants alone at typical dune stands if all the rainfall is held within the root zone and used ultimately for evapo-transpiration without downward percolation.

(4) The condensed water is negligible in the water balance of the typical sandland shrubs although it may play a significant role in the survival of some annual herbaceous species and some bryophytes.

(5) The planting densities of the shrubs studied in this research should be controlled near such a level that the dunes are semi-fixed by plants (i. e., the coverage ranges from about 30% to 40%), with the exception of *Sabina vulgaris* which can form higher density owing to its powerful capability of transpiration control.

## REFERENCES


Chen Wenrui and Zhang Jixian, 1963: Soil water conditions at moving dunes and their relations with sand-fixing and afforestation, *Research on Desert Control*, (5), P246 ~254.

Chen Zhongxin and Xie Haisheng, 1994: Preliminary study on the landscape ecotype classification in Maowusu Sandland and the Biodiversity of its shrub communities, *Acta Ecologica Sinica*, **14**(4) P345~354.

Davis, S. N., 1974: Hydrogeology of Arid Regions, In: *Desert Biology*, Edited by G. W. Brown, Jr., Academic Press, New York and London, P1~28.

Department of Geography, Beijing University, 1983: *The natural conditions of the Maowusu Sands and its improvement utilization*, Science press, Beijing, P1~16.

Dong Guangrong, *et al.*, 1988: The problems of the cause, formation and evolution of the Maowusu Sands. *Science in China* (Series B), **6**: 633~642.

Dong Xuejun, Huang Zichen and Zheng Hailei, 1993: The estimations of leaf areas for some sandy shrubs, *Arid Zone Re-*

*search*, **10**(4) P33～36.

Dong Xuejun, Yang Baozhen, Guo Ke, Liu Zhimao, Alatengbao, Han Song and Zhao Yuxing, 1994: An investigation on the water physo-ecological characteristics of some psammophytes, *Acta phytoecologica Sinica*, **18**(1) P86～94.

Evenari, M., Shanon, L. and Tadmor, N., 1982: Adaptations of plants to desert conditions I & II, In: *The Negev: The Challenge of a Desert*, Second Edition, Harvard University Press, Cambridge, Massachusetts, and London, England, P269.

Guo Ke, Dong Xuejun, Zhao Yuxing and Liu Zhimao, 1996: Variation in transpiration rate of plant cuttings, *Acta Botanica Sinica*, **38**(8) P661～665.

Hillel, D., 1980: *Applications of Soil Physics* Academic Press, New York, P143～146, P213～215.

Hillel, D., 1982: *Negev: Land, Water and Life in a Desert Environment*, New York, Praeger. P103.

Huang Yinxiao and Lin Shunhua, 1974: Water conditions of the sandland plant communities at Toudaohu, Ningxia, *Acta Botanica Sinica*, 16(4) P354～364.

Jiang Ailiang and Chen Jiansui, 1963: A preliminary study on the effects of rainfall on soil water regime in a sandland condition, *Research on Desert Control*, (5)P255～265.

Kaufmann, M. R., 1990: Estimating tree canopy transpiration from measurement of leaf conductance, In: *Measurement Techniques in Plant Sciences*, Edited by Yasushi Hashimoto, Paul J, Kramer, Hiroshi Nonami and Boyd R. Strain, P69～78.

Kobayashi Tetsuo, Masuda Akiyoshi and Kamichika Makio, 1992: Studies on the Evaporation rate of sand dune surface in the Maowusu Sands, In: *Collected Papers of the Maowusu Sands Exploitation and Control Research Center*, (Editor in Chief, Wang Jiaxiang). Inner-Mongolian University Press P127～130.

Li, Bo, Zen Sidi and Hao Guangyong, 1964: Preliminary study on the water ecology of the herbaceous communities in Hulunbeier League, Inner Mongolia, *Acta phytoecologica et Geobotania Sinica*, **2**(1) P70～80.

Liao Rutang and Zhang Wenjun, (Editor in Chief: Wang Jiaxiang), 1992: Studies on the suitable vegetation coverage of drift sand dune in the Maowusu Sands, In: *Collected papers of the Maowusu Sands Exploitation and Control Research Center*, Inner-Mongolian University Press, P93～97.

Liu Yingxin, 1963: Transpiration intensities of the major psammophytes, *Research on Research Control*, (5)P98～108.

Petrov, 1966/1967: *Deserts of Central Asia*. Nanka, Leningrad, Vol. I. Vol Ⅱ.

Shulze, E. D., Hall, A. E., Lange., O. L. and Walz. H., 1982: A portable steady state porometer for measuring the carbon dioxide and water vapor exchanges of leaves under natural conditions. Oecologia, 53: 141～145.

Shuttleworth, W. J. and Wallace, J. S., 1985: Evaporation from sparse crops——an energy combination theory, *Q. J. R. Meteorol. Soc.*, 111. P 839～855.

*Shuttleworth, W. J.*, Edited by David R. Maidment, 1993: *Evaporation*, In: *Handbook of Hydrology*, Chapter 4, P McGraw-Hill, Inc.

Suzuki Masakazu, Editor in Chief and Wang Jiaxing 1992: Fluctuations of groundwater-level and evapotranspiration in the Maowusu Sands, In: *Collected Papers of the Maowusu Sands Exploitation and Control Research Center, Inner-Mongolian University Press* P 120～126.

Xu Qingyun, 1984: Grass species suitable for aerial seeding in Maowusu Sandland, *Chinese Grassland*, (4)34～37.

Yang Baozhen, Dong Xuejin, Gao Qiong, Liu Zhimao and Alatengbao, 1994: Transpiration and water conditions of the Artemesia ordosica communities, *Acta Phytoecologica Sinica*, **18**(2) 161～170.

Zhang Xinshi, 1994: The ecological background of the Maowusu Sandland and the principles and optimal models for grassland management, *Acta Phytoecologica Sinica*, **18**(1) 1～16.

Zhang Xinshi, 1997: *Optimized Ecological Modes of the Grassland Ecosystems in Maowusu* Sandland, Science Press, Beijing.

Zhang Hailei, Huang Zichen and Dong Xuejun, 1992: A study on the physiological ecology of *Artemesia ordosica* and *Cynanchum Komarovii* in Maowusu Sandland, *Acta Phytoecologica et Geobotania Sinica*, **16**(3) 197～208.