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RESEARCH ARTICLE

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Characteristics of soil water consumption of typical shrubs (*Caragana microphylla*) and trees (*Pinus sylvestris*) in the Horqin Sandy Land area, China

Abstract Reforestation is one of the most effective ways to reduce the impacts of desertification. *Caragana microphylla* Lam. and *Pinus sylvestris* var. *mongolica* Litrin have been widely used to stabilize shifting sands in the Horqin sandy land area since the 1980s. However, soil water depletion has been of major concern in *C. microphylla* and *P. ongolica* plantations and in many places current soil moisture cannot meet the demand of growing plants. To determine the water budget of *C. microphylla* and *P. mongolica* plantations, we studied the effect of plantations on soil moisture and assessed the evapotranspiration in plantations of both species. Investigations were conducted at a fenced plot at Wulanaodu (42°29′N, 119°30′E, 479 m a. s. l), located at the western edge of the Horqin Sandy Land area in Inner Mongolia, northern China. Five year old *C. microphylla* and seven year old *P. mongolica* plants were selected from the plantations and transplanted to iron boxes (400 cm × 200 cm × 120 cm) which can drain extra water. Plant spacing of 1 m × 1 m was applied to *P. mongolica*, and two plant spacings of 1 m × 1 m and 1 m × 2 m to *C. microphylla*. The transplanted plants grew for two years in the boxes. Soil moisture from soil surface to a depth 80 cm were measured at 20 cm intervals in boxes every 10 d (2004) or 3 d (2005) during the growing season with a TDR water meter. The evapotranspiration was estimated from a mathematical formula and the characteristics of soil water consumption and evapotranspiration of these two plantations were analyzed. The soil water of *P. mongolica* was more than that of *C. microphylla* at the same 1 m × 1 m spacing. The soil water of *C. microphylla* with the 1 m × 2 m spacing was more than that of the 1 m × 1 m spacing. The evapotranspiration ranged from high to low as follows: *C. microphylla* (1 m × 1 m), *C. microphylla* (1 m × 2 m) and *P. mongolica* (1 m × 1 m) during the growing seasons. The evapotranspiration of individual plants ranging from high to low was *C. microphylla* (1 m × 2 m), *C. microphylla* (1 m × 1 m), and *P. mongolica* (1 m × 1 m) during the growing season. *C. microphylla* grown for five year consumed more water than *P. mongolica* grown for seven years at the same spacing.

Keywords Horqin Sandy Land area, *Caragana microphylla* Lam., *Pinus sylvestris* var. *mongolica* Litrin, soil water storage, evapotranspiriation

1 Introduction

Among all the determinants in the restoration and management of artificial vegetation in sandy lands, the most important are the water-consumption characteristics of psammophytes in semi-arid regions (Nish and Wierenga, 1991; Zhu and Wu, 2003; Jia et al., 2005; Ru et al., 2005; Wang et al., 2005). Both *Caragana microphylla* Lam. and *Pinus sylvestris* var. *mongolica* Litrin are typical sand-fixing plants, which have been widely used to stabilize the shifting sand dunes in the Horqin sandy land area (Cao et al., 2004; Alamusa et al., 2005; Zhang et al., 2005; Yi et al., 2006). In the past, high-density planting was used in sand-fixing vegetation projects to affect rapid protection. Since a decrease in the growth of *C. microphylla* Lam. and *P. sylvestris* var. *mongolica* Litrin was observed in part of the vegetation area over time, many scientists have come to believe that excessive consumption of soil moisture is one of the main causes of this decline (Cheng et al., 2004; Cheng et al., 2005; Gerile et al., 2006; Lu et al., 2006). One of the major issues was

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how to make suitable use of limited soil moisture to maintain normal growth of sand-fixing plants. Focused on this issue, many studies have been carried out on soil moisture changes after the establishment of artificial sand-fixing vegetation (Feng et al., 1995; Bemdtsson and Nodomi, 1996; Southgate and Master, 1996; Dong et al., 1997; Fu et al., 2001; He and Zhao, 2004; Wei and Wu, 2006). Lu et al. (2006) studied soil moisture of artificial sand-fixing vegetation in the Mu Us sandy lands and found that available soil water gradually decreased during the growth of the vegetation. Zhang et al. (2005) also reported that soil moisture of artificial sand-fixing vegetation reduced annually in the Horqin sandy land. In the past, most research was focused on dynamic changes of soil moisture in the areas with artificial vegetation, while fewer studies of water consumption of specific vegetation areas were conducted. Only a small number of studies focused on typical vegetation in different geographic areas (Si et al., 2005; Liu et al., 2006; Zhang et al., 2006). Accurate calculation of vegetation evapotranspiration will play an important role in establishment and intensive management of artificial sand-fixation vegetation, which is also used to prevent a decrease in the amount of water caused by its unbalanced use.

By planting in growth chambers, typical dune-fixing shrubs (*C. microphylla* Lam) and trees (*P. sylvestris* var. *mongolica* Litrin) were studied in the Horqin sandy lands. Given the theory of soil moisture balance, the objectives of our study were: 1) to calculate the effect of growth and development of *C. microphylla* Lam and *P. sylvestris* var. *mongolica* Litrin on soil moisture and 2) estimating evapotranspiration in vegetation zones of *C. microphylla* Lam and *P. sylvestris* var. *mongolica* Litrin.

2 Materials and methods

2.1 General situation of experimental field

Our experimental field was located at Wulanaodu region (119°30′E and 42°29′N, 479 m a. s. l), western edge of the Horqin sandy land area northeast Inner Mongolia, China. The area has a temperate, semi-arid climate with an average annual wind speed of 4.2 m/s and average annual winds of 7–8 grade level, occurring for 65–70 d. The average annual temperature is 6.2°C and the frost-free period is 140 d. The average annual precipitation is 284.4×82.4 mm (1982–2003). The lowest annual precipitation ever recorded is 136.9 mm and the average aridity is 1.99. The distribution of precipitation during the year is uneven and falls mainly from June to August, accounting for over 70% of annual precipitation. March receives only about 10% of the annual rainfall. The annual evaporation is 2000–2500 mm/year. Its landscape is a broad sandy land region, with sand dunes and wetlands. Semi-mobile dunes, fixed, semi-fixed sand dunes and lowland between sand dunes are the usual habitats of plants. Our experimental field was in an area of artificial sand-fixing vegetation of *C. microphylla* Lam. and *P. sylvestris* var. *mongolica* Litrin, which was in the past a more flat sandy area. Xerophytes such as *Pennisetum centrasiaticum*, *Cleistogenes squarrosa*, *Setaria viridis* and *Agriophyllum squarrosum* are found in this artificial community of sand-fixing vegetation.

2.2 Materials and methods

Three year old *C. microphylla* and five year old *P. mongolica* plants from the Horqin sandy lands were selected and transplanted to iron boxes (400 cm× 200 cm×120 cm) in the spring of 2002, which could drain extra water (Fig. 1), i.e., the boxes contained water collecting tubes, 5 cm apart, with 3 mm-diameter drilled holes to drain extra water. These water-collecting tubes were wrapped in 100-size gauze to prevent blocking by sand. Above and around the water collecting tubes in the boxes were filled with a 20 cm layer of gravel. The tubes, protruding 20 cm outside the bottom of the box, were the drainage outlets. Below each draining outlet, we installed a water container (funnel + measuring cup) to calculate leakage of water; soil filled the inside of the box, up to 5 cm from top edge of the box. The boxes were placed under ground, with only the upper part of the boxes 3–5 cm above the ground in order to prevent the soil being mixed

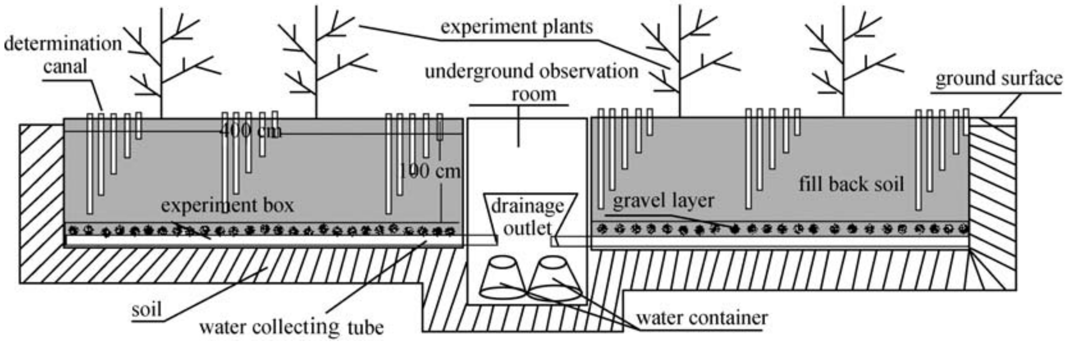

Fig. 1 Sketch map of growth boxes on species and setting

with surface water formed by precipitation. An underground observation room, a space in which the amount of water seepage could be recorded, was established in the direction of the water collecting tubes.

Four boxes were set among the corresponding plants in the region in order to imitate closely the internal state of the plant communities. That is, we placed the boxes with *C. microphylla* in the interior of the area of *C. microphylla* vegetation, where the size of the vegetation area was about 130 m×70 m. The boxes with *P. mongolica* were placed in the interior of the *P. mongolica* vegetation, where the size of the vegetation area was about 40 m×60 m. The age and height of all plants in fixation vegetation area were similar to those of the experimental plants.

Four treatments were conducted. Two plant densities: 8 cluster/box (1 cluster/m^2, with 1 m×1 m spacing, marked C1) and 4 cluster/box (1 cluster/2 m^2, 1 m×2 m, marked C2) were applied to *C. microphylla*. A plant density of 8 cluster/box (1 plant/m^2, 1 m × 1 m spacing, marked P) was applied to P. *mongolica*, with an empty control box (marked CK1), placed in a peripheral experimental field, without shrubs and trees and grass grew naturally in the box. In each of the planting boxes, three groups of PVC pipes with a diameter of 6 cm, open-ended on both sides, were pre-placed vertically at different depths. Each group included individual PVC pipes at depths of 5, 20, 40, 60 and 80 cm. PVC pipes were sealed with rubber plugs,. Probes of a time domain reflectometry (TDR) soil moisture meter (Model: MP-160, Meridian, Australia) were inserted into the soil of each pipe, measured three times for soil moisture content per unit volume soil.

The tests in 2004 were carried out from May 1 to October 10, at about 10 d intervals. The observations in 2005 were from April 23 to November 3, with a 3 d interval. Precipitation data were recorded by the meteorological station in Wulanaodu (the distance to the plot was within 500 m). Soil leakage from the boxes was determined by water collected from the drainage outlets, with a 30 d measuring interval. Conversion values were established according to the planting area of the boxes.

2.3 Formula and analysis

The formula for soil water storage capacity is as follows:

$$E = M_{\mathrm{w}}RH,\ M_{\mathrm{v}} = M_{\mathrm{w}}R,\ E = M_{\mathrm{v}}H \tag{1}$$

where E is soil water storage capacity (mm), M_{v} soil volume water content (%), H soil thickness (mm), M_{w} soil weight water content (%), R soil bulk density (g/cm^3).

Evapotranspiration is the sum of plant transpiration and evaporation of surface water per unit area, i.e.,

$$ET = P - S - Q \tag{2}$$

where ET is evapotranspiration (mm), P the cumulative precipitation over a certain period (mm), S the changing value of the soil water storage over a certain period (mm) and Q soil water leakage over a certain period (mm).

Because tests were carried out inside the box, there was no loss of surface water and the exchange of water occurred beside the soil in the box. Statistical software, such as Microsoft Excel XP and SPSS 11were used in data processing.

3 Results and analysis

3.1 Change in soil water storage capacity

Soil water storage capacity at varying depths of 0–80 cm was observed during the growing season. The results show that soil water storage capacity varied over time (Fig. 2). Major changes in soil water storage capacity in 2004 can be divided into, 1): a stable period (from May to June), during which soil water storage capacity was relatively stable; 2) a fluctuating period (from June to August), during which marked fluctuations occurred in soil water storage capacity; this period had dramatic changes in soil water storage capacity; 3) a period of decline (after August), during which soil water storage capacity of this period showed a gradually decreasing trend. The trend in 2005 was similar to that in 2004, with only slight differences in temporal distribution. The trend was as follows: a smooth period (from late May to early July); a fluctuating period (from early July to mid-August); a period of decline (after mid-August). The differences in changes of soil moisture were closely related to the precipitation distribution during the same period.

Comparing the different treatments, we conclude that soil moisture conditions of C2 were better than those of other treatments in late July, 2004, when the soil water storage capacity was very high, about 120 mm, while the soil water storage capacity of other treatments maintained their level at around 70–80 mm; the soil water storage capacity of C2 decreased after late July and was lower than that of other treatments.

During the growing season, a similar trend showed in soil water storage capacity of other treatments; only after August did a slight difference occur and the capacity of C1 almost equaled that of P. In 2005, CK maintained the same high soil water storage capacity all year. Soil water storage capacity of CK during the growing season was higher than of other treatments. Soil water storage capacity of P was slightly lower than that of CK, but for most of the time it was higher than that of C1 and C2. Water storage in C1 was at a minimum for most of the time, especially in the period after July and significantly lower than that of other treatments.

Vertical changes in soil moisture content showed an increase with depth (Table 1). The maximum occurred at a depth of 80 cm. The average soil moisture content reached 13.35% and 16.13% in 2004 and 2005. Comparison with

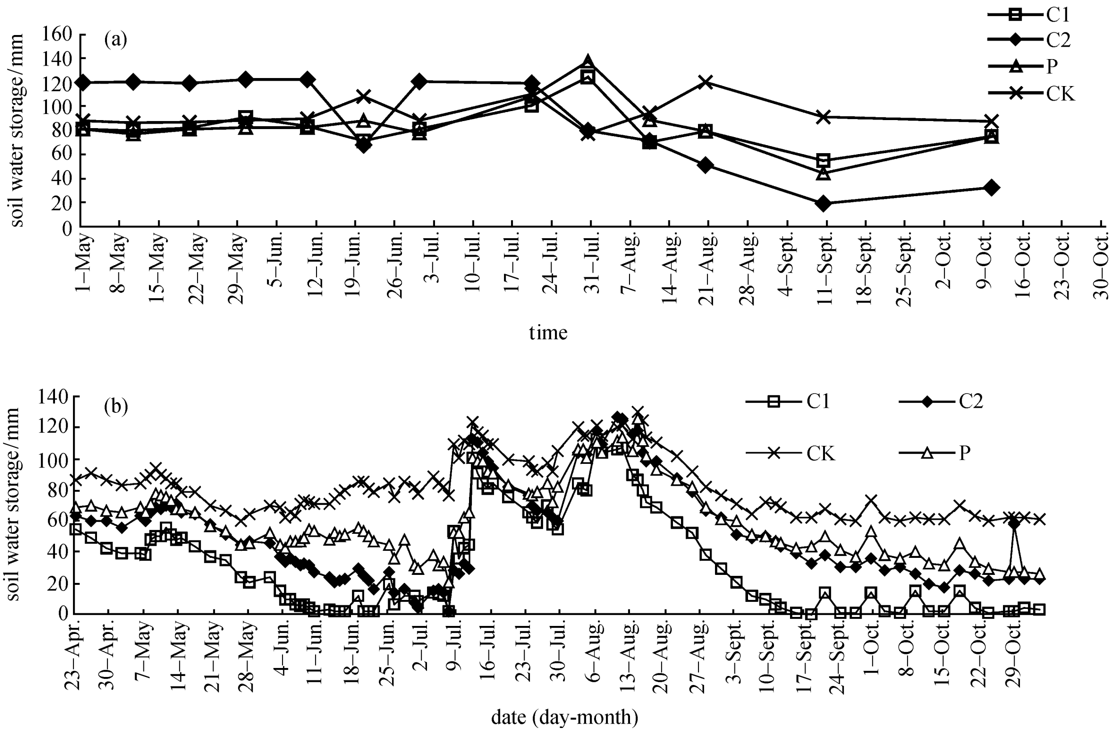

Fig. 2 Changes in soil water storage capacity

Table 1 Comparison of soil water content between different type of plantations at various depths (unit: %)

year	depth/cm	C1	C2	P	CK
2004	5	5.90±0.59	6.31±0.39	6.65±0.50	7.19±0.32
	20	6.55±0.64	7.07±0.46	7.27±0.58	6.58±0.71
	40	7.50±0.79	8.02±0.61	8.40±0.38	8.60±0.74
	60	9.58±1.37	8.81±0.62	9.26±0.31	10.99±0.38
	80	15.25±2.26 a	11.06±0.69 bc	9.22±0.49 c	13.35±0.94 ab
2005	20	5.00±0.48 b	6.22±0.46 ab	6.77±0.46 ac	7.18±0.35 a
	40	4.51±0.49 c	5.48±0.43 c	6.77±0.38 b	8.56±0.24 a
	60	4.74±0.45 d	6.72±0.43 c	7.76±0.33 b	10.52±0.22 a
	80	5.16±0.35 d	8.01±0.46 c	9.64±0.24 b	16.13±0.31 a

Note: Rows with different lowercase letters were significantly different at $p < 0.05$, according to Duncan's multiple range test.

different treatments showed that only soil moisture at 80 cm depth showed differences in 2004, when C1 and CK had significantly higher moisture content than P and that of C1 was significantly higher than that of C2. Different treatments in 2005 at all levels of depths were different. The order was CK, P, C2 and C1, where at depths of 60 and 80 cm, significant differences were found.

3.2 Comparison of soil leakage

Leakage in soil moisture gradually increased from the early growing season, with a maximum in July or August and then gradually decreased. The leakage in October was close to that in May, ranging from 0 to 9.68 mm/month; annual comparison of leakage showed that the highest leakage occurred in the control (CK) in 2004 (32.65 mm/year) and 2005 (23.13 mm/year), followed by P of 24.59 mm/year and 16.67 mm/year, C2 with 15.75 mm/year and 13.51 mm/year in third place and C1 with the least at 10.13 mm/year and 12.22 mm/year (Fig. 3). Under the same density conditions, soil moisture leakage of *P. mongolica* vegetation was higher than that of *C. microphylla* vegetation. Increased density in *C. microphylla* vegetation resulted in reduced leakage.

3.3 Changes in evapotranspiration

3.3.1 Characteristics of changes in evapotranspiration

During the growing season, evapotranspiration in our vegetation zone showed a gradual increase after the period

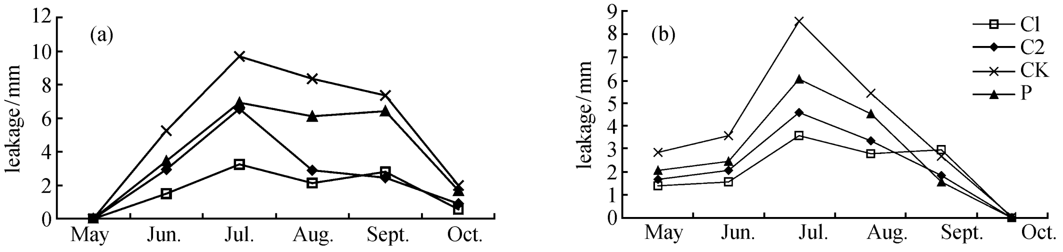

Fig. 3 Soil water leakage of different plantations over time. a: 2004; b: 2005.

of leaf-expansion; the highest occurred in the period of July to August (2004) and the period of August to September (2005) and then gradually declined (Fig. 4). Monthly changes of evapotranspiration during the growing season ranged from 4.44 to 125.31 mm (2004) and from 1.44–140.50 mm (2005). Seasonal changes in evapotranspiration and precipitation trends were synchronized. If we were to take the results of 2004 as an obvious example, correlations between C1, C2, P, CK and precipitation of the same period were very high, with coefficients of 0.87, 0.80, 0.66 and 0.94 ($n = 7$, $t = 0.66$). There were some different changes in evapotranspiration in 2005. During the period of July to August precipitation was 117. 9 mm, while evapotranspiration was only 35.86–67.56 m, which does not show a marked increase. Relevant weather data showed that precipitation during this period occurred for 21 d, cloudy conditions prevailed for 17 d and total low light intensity for 38 d. Low light intensity and higher humidity significantly reduced plant transpiration and evaporation from the land surface, which may be one of the more important reasons for asynchronous behavior between precipitation and evapotranspiration.

3.3.2 Accumulation of evapotranspiration during growing season

The accumulated evapotranspiration of C1 was the highest (2004, 2005) throughout the growing season. The order, from high to low, was C1, C2, P, CK, ranging from 199.77 mm (CK) to 309.53 mm (C1) (2004) and from 299.07 mm (CK) to 363.10 mm (C1) (2005) (Fig. 5). In comparison, the corresponding values were as follows: C1 (53.57 mm), C2 (113.05 mm), P (111.90 mm), CK (99.30 mm). Evapotranspiration of plants per cluster were calculated according to seasonal evapotranspiration for different species and different plant densities (Fig. 6).

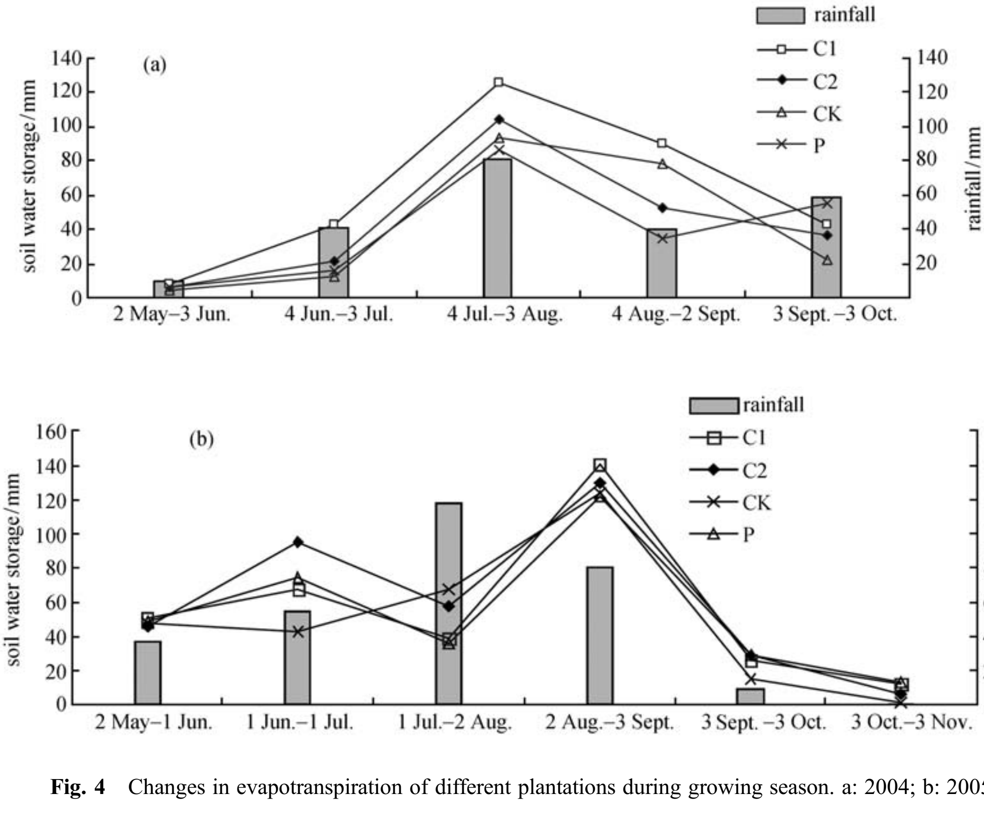

Fig. 4 Changes in evapotranspiration of different plantations during growing season. a: 2004; b: 2005.

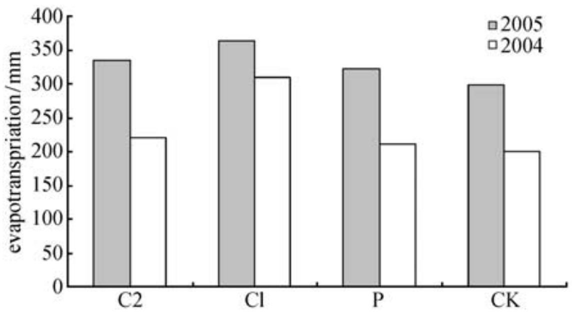

Fig. 5 Accumulated evapotranspiration in different plantations during growing season

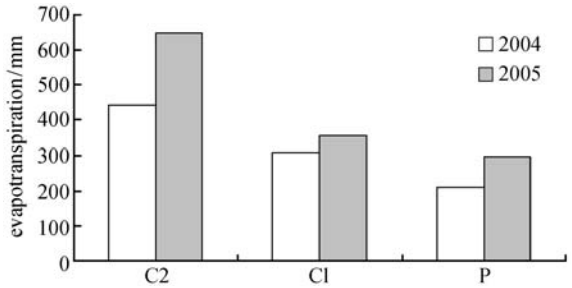

Fig. 6 Accumulative evapotranspiration of single plant of different plantations during growing season

During the period from May 2 to October 3, the order, from high to low, of evapotranspiration of plants per cluster was C2 (*C. microphylla*, cluster/2m^2), C1 (*C. microphylla*, cluster/m^2), P (*P. mongolica*, cluster/m^2). Evapotranspiration of various types in 2005 was higher than in 2004. During the period from May 2 to October 3, evapotranspiration of plants per cluster in 2005 were: C2 (645.43 mm), C1 (356.56 mm), P (297.64 mm), while evapotranspiration of plants per cluster in 2004 were: C2 (442.80 mm), C1 (309.53 mm), P (210.77 mm). Changes of evapotranspiration of plants per cluster showed that evapotranspiration of *C. microphylla* with a density of cluster/2 m^2 were significantly higher than that of cluster/m^2.

4 Discussion

4.1 Factors of change in soil moisture

Changes in characteristics of soil water storage capacity over time occurred for different fixing-sand species and densities. These are closely related to plant transpiration and precipitation (Bai et al., 2004; Zhao et al., 2004; Wang et al., 2005; Zhang et al., 2005). Obvious changes of soil water storage capacity caused by increased water consumption in plant transpiration occurred from June to August. At the same time, precipitation in this period accounted for more than 70% of the total annual rainfall and drastic changes were shown in soil water storage. Precipitation gradually reduced after September, but suitable light and temperature conditions for the plants continuously consumed soil moisture, which lead to its downward trend. Although the distribution of precipitation affected soil water storage capacity, its effect was not immediate but delayed over time (Jiao, 2001). Statistical analysis of the distribution of precipitation and soil water storage capacity showed significant correlations ($C1=0.6875$, $P=0.7090$, $n=13$, $t=0.514$) between 15 d later soil water storage and precipitation occurring in quadrates, although significant correlation was not detected in all quadrates. However, in many cases, the distribution of precipitation was one of the main factors affecting changes in soil water storage. It was shown in the temporal characteristics of soil moisture. We found that temporal differences of soil moisture changes (stable, fluctuating and declining periods) in 2004 and 2005 were closely related to precipitation distribution. Previous studies have shown soil droughts in arid and semi-arid areas and much more soil droughts in mature, artificial vegetation (Jiao, 2001; Cheng et al., 2005; Wang et al., 2005), i.e., there was a soil layer with an extremely low water content, where the deep soil moisture could not be added during periods when precipitation was concentrated.

Soil drought at 70–120 cm deep usually occurred in the 15-year-old *C. microphylla* vegetation with 1 m×1 m planting density in the western part of the Horqin sandy land area. The so-called "soil drought" cannot be added by precipitation (Alamusa et al., 2005). Soil moisture leakage was observed in our experiment, which showed that there was a certain amount of water supplied to the deep soil in periods of abundant precipitation in the 5-year-old *C. microphylla* and 7-year-old *P. mongolica* vegetation. Thus soil drought did not occur. Soil leakages under the various treatments during the growing season were significantly different. The highest leakage of *C. microphylla* was the control (CK), 3.19 (2004)–1.89 (2005) times that of C1 with the lowest density of 1 m×1 m. Accumulated leakage in C1 was more than 22.40 mm (2004)–10.91 mm (2005). The amount of leakage reflected the changes in vegetation on soil moisture; reduced leakage suggests that surface plants consumed much more soil water.

4.2 Plant species, density and soil water consumption

Plant species determine their water consumption characteristics. Comparison between different plant species showed that for the same density, soil water storage capacity of 7-year-old *P. mongolica* (1 m×1 m) was higher than that of 5-year-old *C. microphylla* (1 m×1 m and 1 m×2 m spacing). For *P. mongolica*, both accumulated evapotranspiration and plant evapotranspiration per cluster are lower than for the *C. microphylla* vegetation. Water consumption characteristics of different species are related to specific conditions. *C. microphylla* could reach a stable growth period after 5 to 7 years, but for *P. mongolica* this is still an early growing stage. So comparison of soil moisture and evapotranspiration can only be described for specific age conditions. Evapotranspiration of *C. microphylla* is higher than that *P. mongolica* at the early growing stage.

Plant density can be guided according to water consumption characteristics of plants. *P. mongolica*, at 1 m×1 m, spacing causes imbalances in soil moisture over time. There is a controversy about a suitable initial planting density of *P. mongolica*. Zeng et al. (2000) used a rule of self-thinning and obtained a suitable initial planting density of 3000–3500 plants/hm^2 (equivalent to 2.85 to 3.3 m^2/plant area). Yi et al. (2006) concluded that a suitable initial planting density was 2800plants/hm^2 in Zhanggutai, Liaoning Province, which should then be thinned to 2100 plants/hm^2 (equivalent to 4.76 m^2/plant area) over time. Therefore, when *P. mongolica* is used as fixing-sand vegetation, a gradual thinning method should be employed. At the beginning, a high-density planting can achieve a rapid fixing-sand effect; after that, strict control over stand density must be maintained through thinning (Jiao, 2001; Yi et al., 2006). We found that the higher density of plants consumed a larger amount of soil moisture by comparing evapotranspiration of *C. microphylla* vegetation at different planting densities, which means that soil moisture content of *C. microphylla* at 1 m×1 m planting spacing was lower than 1 m×2 m and evapotranspiration per unit area was higher than that at 1 m×2 m spacing. Rapid growth of *C. microphylla* after planting consumed more soil moisture and led to soil depletion. Appropriate density of *C. microphylla* should be used to maintain a correct soil moisture balance. The initial density of *C. microphylla* vegetation can be controlled at the level of 1 m×1 m spacing in the Horqin sandy land area. Gradually thinning to a level of 2 m×2 m will maintain the basic balance of soil moisture (Alamusa et al., 2005). Water-consumption characteristics of plants are a key to the rational use of soil moisture (Feng et al., 1995; Wang et al., 2005). Plant species and planting methods should be chosen based on water consumption characteristics of plants, which is important and of theoretical and practical significance to establish stable artificial fixing-sand vegetation.

4.3 Environmental factors of evapotranspiration

It was found that evapotranspiration in 2004 was significantly lower in 2005, both in monthly and total accumulated evapotranspiration. Precipitation in 2005 reached 299.7 mm during the growing season while in 2004 it was 231.5 mm. In terms of adequate precipitation, soil moisture could be maintained at a high level to guarantee the transpiration of water consumption of plants. Growth of plants becomes more vigorous when more transpiration water is consumed. As well, a corresponding increase of surface evaporation has led to an increase in total evapotranspiration. Relatively less precipitation reduced soil moisture content in 2004 and resulted in a soil drought during the year and reduced transpiration of water consumption of plants. Simultaneously, good lighting and appropriate temperature promoted evapotranspiration. We found that much precipitation and higher soil moisture content occurred during the period from July to August of 2005, but a marked increase in evapotranspiration has not followed. Reduction of surface evaporation and transpiration of plants was caused by more rain according to climate records.

4.4 Analysis of the water balance

Accumulated evapotranspiration during the growing season of plants was higher than precipitation during the same period. Soil water storage failed to attain a balanced state; the soil water storage during the late growing season was less than that at the initial stage. If we take soil water storage capacity of C1 in 2004 as an example, it is shown that soil water storage capacity of 120.34 mm at the initial stage (May) decreased to 32.55 mm during the late growing season, i.e., this is due to the consumption of the original stored soil moisture and reduced soil water storage capacity. However, considering the entire year, in May, 2005 soil and water storage capacity had been restored and during the non-growing season, precipitation added to the soil water storage capacity. Therefore, studies on soil moisture balance in vegetation should take into account soil moisture accumulation during the non-growing season, especially in the cold northern areas. Changes in soil moisture during the winter still need further study.

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