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The dynamics variation of soil moisture of shelterbelts along the Tarim Desert Highway

WANG YongDong[1, 2], XU XinWen[1†], LEI JiaQiang[1], LI ShengYu[1], ZHOU ZhiBin[1], CHANG Qing[1], WANG LuHai[1], GU Feng[3], QIU YongZhi[3] & XU Bo[3]

[1] Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China;
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China;
[3] Tarim Branch, PetroChina Company Limited, Korla 841000, China

We studied the variation of soil moisture as well as its regularity over the irrigation cycle at shelterbelts along the Tarim Desert Highway at different site types and different planting years. The results show that: (1) There is an obvious temporal variation of soil moisture within a typical irrigation period in shelterbelts along the Tarim Desert Highway, and the soil water storage varied linearly with the number of days after irrigation. Along the direction perpendicular to the soil top, the soil profile can be divided into four layers and each shows different dynamics of soil moisture variation, including the quickly changing layer (0—20 cm), the active layer (20—60 cm), the weakly layer (60—100 cm), and the regulated layer (under 100 cm). (2) Both the soil moisture and soil water content decreased gradually with the number of planting year, while the soil water deficit increased. It indicates that shelterbelts along the Tarim Desert Highway can retain the water accumulated from previous years. (3) The soil water storage of harden sand is the maximum among all types of sites. Specifically, it is about 1.58 times higher than that of longitudinal dune, 1.15 times higher than clay, and 1.43 times higher than flat sand. Its soil water deficit was over 900 mm.

shelterbelts along the Tarim Desert Highway, dynamics of soil moisture, soil water storage, soil water deficit

Moisture is one of the crucial factors in studying and rebuilding the desert[1]. Soil moisture is particularly important in desert ecology system. It not only reveals the relation between surface water and groundwater and plays an important role in the formation, transition and consumption processes of water resource[2], but also is one of key factors determining the stability, the well-balanced construction and the function of desert ecology systems. Moreover, soil moisture is also a major limiting factor for the plant growth and restoration in arid environments[3−6]. It is clear that the increase of soil moisture can cause an increase in water dissipation, whereas the decrease in soil moisture can affect the vegetation growth and even lead to their death. Therefore, in one hand, the spatiotemporal pattern of soil moisture determines the distribution of regional vegetation. On the other hand, it is affected by the vegetation growth as well as the root water uptake and soil evaporation[7]. A systematic research about the dynamics changes of regional soil moisture can reveal not only the utilization intensity of vegetation as well as the action law to some extent[8] but also the physical insight about the moisture process and the soil moisture movement[9−11]. The study about the soil moisture dynamics is necessary in quantitatively relating the hydrologic dy namics to ecological patterns and processes[12]. Therefore, the spatial-temporal pattern of soil moisture has attracted more and more attention around the world.

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†Corresponding author (email: sms@ms.xjb.ac.cn)
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The shelterbelt along the Taklimakan Desert Highway across the shifting desert is 436 km long. It plays the crucial role in protecting the highway from wind damages. The dynamic change of soil moisture as well as the bearing capacity of irrigation water in the harsh environment is important for growth of shelterbelts along the Tarim Desert Highway thereafter being a hot topic. During the last decade an increasing number of studies have been published focusing on the transport and simulation of soil moisture and salt[13,14], the stability of shelterbelts along the Tarim Desert Highway[15], the choice of irrigation techniques, and the application of irrigation scheduling[16]. However, most of these studies ignored the dynamic characteristic of soil moisture, specifically, the change of soil moisture deficit at different site as well as at different planting years. In this study, we attempt to investigate and analyze the spatiotemporal distribution of soil moisture on the basis of the data of shelterbelts along the Tarim Desert Highway over the years. The results are expected to provide some scientific insights on the plant growth of the shelterbelts along the Tarim Desert Highway as well as the management of groundwater resources. In addition, these results can also shed a light on the sustainability of shelterbelts along the Tarim Desert Highway.

1 Materials and methods

1.1 The research areas

The experiment was conducted at the Tazhong region (39°00′N, 83°40′E) in the Taklimakan desert. The area remains with a special temperate desert land, higher temperature and dry season, the annual average temperature is generally 11.1－12.4℃, with an annual average temperature in the summer time of 26.8－28.2℃. The annual accumulated temperature (⩾10℃) ranges from 3900 to 4300℃; the total sunshine period is 2800－3200 h; the frost-free period is from 180 to 270 days. The rainfall duration is as long as 4 months from May to August; the annual evaporation is from 2000 to 3639 mm, the annual average relative humility is just 35%－55 %.

1.2 Experimental method

The spatial-temporal dynamics of soil water content was investigated within 31.8 km shelterbelts of the desert highway located around the Taklimakan Desert Research Station. Three plant species, i.e. *Tamarix, Haloxylon* and *Calligonum* L, respectively, were selected to construct the shelterbelts at both sides of the Tarim Desert Highway. The row distance of shelterbelts is 1 m while mixed among rows with spacing in the rows about 1 m×2 m and 72－78 m wide.

The experiment consists of two parts: The first is the analysis of the dynamics of soil moisture based on the irrigation frequency. The soil moisture was measured right before and after the saline irrigation as well as 2 days before and after the irrigation; the second was to analyze the soil moisture dynamics at different planting years and different shelterbelts sites. Specifically, experimental sites were divided into 9 plots according to their location, soil characteristics, and planting year of shelterbelts. Then, 9 neutron probes access tubes were installed in each plot to a depth of 360 cm. The measurements of soil water content were made at 10 days intervals over the whole growing season. The measurements started from 0.2 to 360 cm at depth intervals of 20 cm. The soil water content of the upper profile was measured in shelterbelts by Lnw-50A neutron probe. Because of the difference in neutron velocity at different soil depths, two *in situ* calibration curves were made for soil depth range (⩽30 cm) and (＞30 cm), respectively (Figure 1).

1.3 Calculation method

Soil water storage (WC) was calculated to determine the profile of volumetric water content (V_s) of soil[17]. Both WC and the soil water deficit amount (DWC) are defined by

$$\mathrm{WC}=V_s\times H\times 10, \quad (1)$$

$$\mathrm{DWC}=\mathrm{SFC}-\mathrm{WC}, \quad (2)$$ [18]

where V_s is the volumetric water content (mm), H is the depth of soil (cm), and SFC is the soil field capacity (mm).

SFC was measured by the indoor J. C. WILCOX method. The bulk density of soil layer was measured by the cutting ring method and repeated three times. All climatic data, such as rainfall and evaporation were provided by a weather station near the field.

2 Results and analysis

2.1 The dynamics of soil moisture in shelterbelts based on the irrigation frequency

(i) The temporal variation of soil moisture based on the irrigation frequency in shelterbelts.

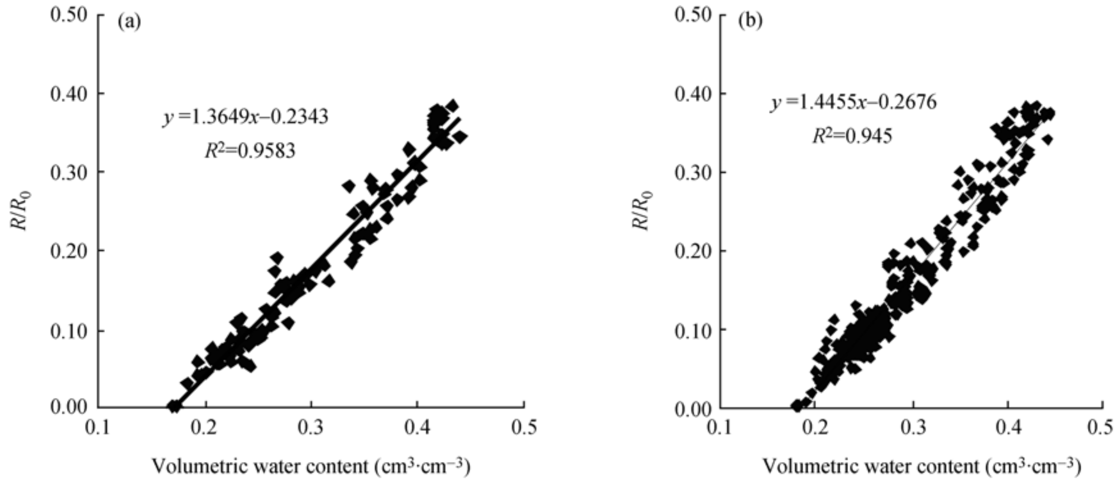

Figure 1 *In situ* calibration curves neutron probe. (a) ≤30 cm; (b) >30 cm.

Because of the high evaporation and atrocious environment in the Taklimakan Desert, water needed for plant growth at shelterbelts is via drip irrigation. Consequently, researchers suggested that shelterbelts should be irrigated at intervals of 15—10-day during April, May, September, October as well as from June to August, respectively. Each irrigation time is about 8—10 h. Therefore, the soil moisture temporal dynamics should depend on the irrigation frequency and is affected little by the intraseasonal dynamics of soil moisture during the whole growing season.

To analyze the dynamics change of soil water storage, we measured the soil moisture data within a soil depth of 200 cm for 2 days based on the irrigation frequency (15 d). Soil water content was 120.47 mm at the start of irrigations and increased to 201.24 mm right after irrigation. In addition, the soil water storage has been found to decrease to 198.52 mm after 2 days. This decrease in soil moisture might be due to the evaporation of soil and transpiration of plants. The depletion extent of soil moisture mainly depends on the above factors, while other factors that involve in the air evaporation, such as the radicalization, the air temperature, the soil moisture and the wind speed, affect the soil moisture too. In addition, on the other hand, soil moisture factor is explicitly considered as the size of soil moisture, this is an initial factor for transportation of soil moisture. Obviously, the period of soil water depletion should be consistent with that of irrigation. Correspondingly, the experimental data of the change of soil water storage have been plotted over the drip irrigation period, i.e., 15 d. Particularly, the soil water storage was as low as 114.41 mm at the end of the irritation period and rises to the initial value at the start of the new irritation period. A statistically significant linear relationship was found between the day after irrigation and the soil water storage, i.e., $y = -3.3366x+205.25$ ($1<t\leqslant 15$), as shown in Figure 2. Here, y is the soil water storage and x the day after irrigation. Similar results were reported by Huang et al.[19] under the rainfall irrigation condition.

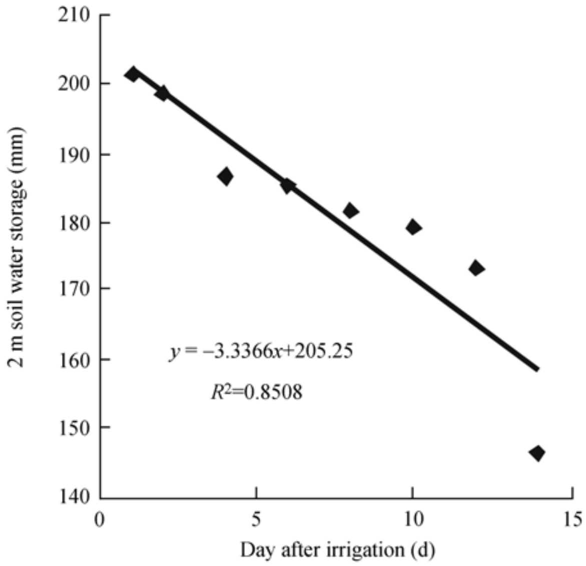

Figure 2 The temporal dynamics of irrigation frequency.

(ii) The spatial variation of soil moisture. The soil moisture has been found to vary significantly at different sites. The observed variation may result from the variations in irrigation amount, the quantity of root, the distribution of roots, the conditions of bulk soil and weather[20]. There already have been a series of studies in which the change of soil moisture has been measured at different depths of soil and different soil profiles[21−23].

The soil moisture varied significantly with the soil profile depth as a consequence of the special environmental conditions in shelterbelts along the Tarim Desert Highway. Even though soil layers change significantly at different soil layers over different sites, their dynamics follows the same rule. Particularly, in this study, a definite relationship between the dynamics of soil moisture and irrigation amount has been proposed at different sites and different layers. Specifically, along the direction perpendicular to the horizons (Figure 3), there are four layers with different soil moisture conditions: (1) the quickly changing layer (0—20 cm), in which the soil moisture is affected mostly by the evaporation and other external factors. Here, the dynamics of soil moisture change was well revealed. (2) the active layer (20—60 cm), in which the moisture in the soil layer is determined by the soil moisture diffusion and its distribution. The change in the soil moisture was obvious; (3) the weakly changing layer (60—100 cm), in which the water content is influenced by the root water uptake as well as the water diffusion and the distribution; and (4) regulated layer (under 100 cm), in which the environmental conditions and groundwater have little influences on the soil moisture. As a result, the soil moisture kept a stable value.

2.2 The variation of soil moisture with the planting years

The soil moisture necessary for the growth of shelterbelts along the Tarim Desert Highway mainly comes from two resources, i.e., rainfall and irrigation. However, due to the high evaporation rate, about 11—40 mm rainfall is evaporated on the average each year. In addition, because the groundwater table is less than 10 m in the experimental region, the groundwater is very impossible to be the primary source for surface water supply. Therefore, most soil moisture comes from the irrigation water. Figure 4 shows the variation of soil moisture as a function of the planting year. We can see that the moisture decreases significantly with the planting years, i.e., $V_{s_1} > V_{s_4} > V_{s_7} > V_{s_{10}}$ in which V_s is the volumetric soil moisture (the subscript denotes the planting year). These results are consistent with those reported by Li[24] and A lamusa[25] et al., which shows that the soil water content of sand-fixing vegetation decreased, especially in the deeper part of soil profile (>100 cm), after 9 or 10 years.

The annual average variation of soil water content is between 1.8% and 7.8% for the first planting year, 0.34%—2.05% for 4 years, 0.39%—2.03% for 7 years, and 0.8%—2.52% for 10 years. It can be inferred that the annual variation of soil moisture decreases with the planting years. Particularly, except for the first planting year, the soil water content for all other panting years shows two peaks. Specifically, a peak was around 60 cm at the soil profile. It may be because the water evaporation becomes rather limited at the soil layer depth of 40—60 cm[22]. The soil water content beyond the soil

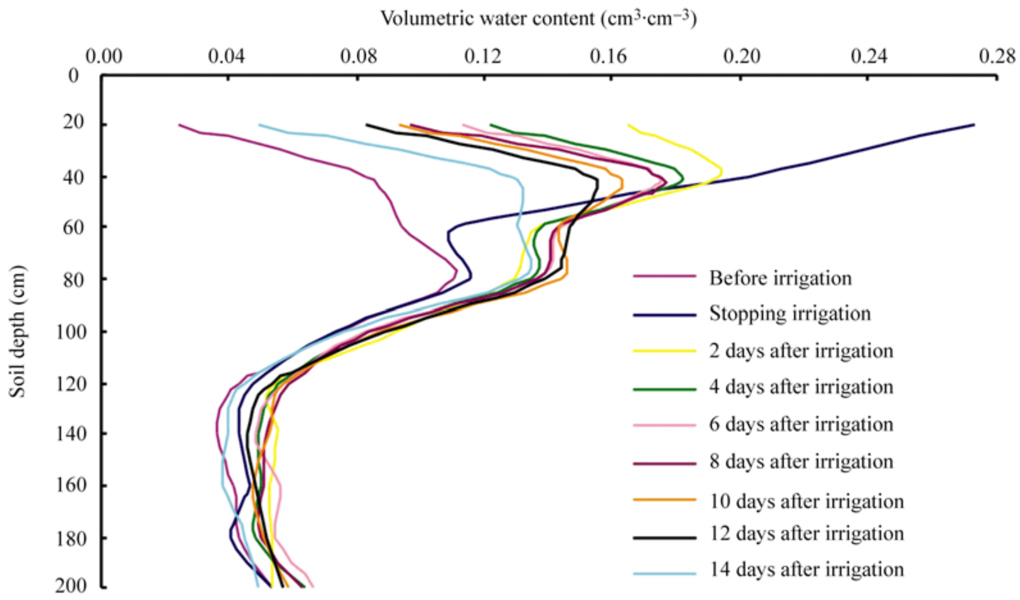

Figure 3 The vertical dynamics of soil moisture with irrigation frequency.

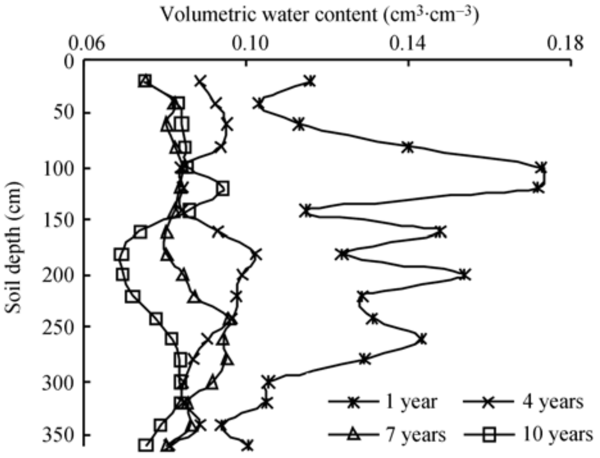

Figure 4 The dynamics of soil moisture with planting years.

depth of 60 cm, which can be affected by external environment thereafter changed significantly, was not analyzed. The other peak appeared below a 100 cm depth of soil profile. The location of this peak is 180 cm for the 4th planting year, 240 cm for the 7th planting year, and 280 cm for the 10th year. Particularly, the appearance of this peak indicates that there is a minimum value in soil moisture in soil profiles. This minimum value indicates the actual moisture status of this layer, which is taken as the index for the growth of shelterbelts as a matter of the fact that the moisture under 100 cm of soil profile is less influenced by external environment factors. As a result, the water at this minimum moisture position should be the water taken up by root and used for plant growth. The position of minimum water content is 140 cm for the first planting year, changes to 160 cm at the 2nd and 4th years, and becomes 180 cm for the 10th year. These results indicate that the depth of water consumption increased with planting year in shelterbelts.

Table 1 shows the monthly variations of soil hydrology effect indexes during different planting years, including the volumetric soil moisture, the soil water storage, and the soil water deficit. Moreover, the soil water storage decreases with the planting year in the order of $WC_{10}<WC_7<WC_4<WC_1$ in which WC is the soil water storage while the subscript denotes the planting year. In contrast, the water deficit amount increases with the planting year. i.e., $SWD_{10}>SWD_7>SWD_4>SWD_1$, in which the subscript denotes the planting year. In addition, the variation range of soil water deficit amount was 2—26 mm, 7—32 mm, 2—19 mm and 9—58 mm for the 1st, 2nd, 4th, and 10th planting years, respectively. Therefore, the amount of demanding water of shelterbelts along the Tarim Desert Highway increased with the planting year, and more and more depended on accumulation water in the former year.

2.3 The variation of soil moisture at different types of sites

As shown in Figure 5, the variation of soil moisture in the longitudinal dune, the flat sand, the clay, and the harden sand exhibited the same trend. Specially, the minimum of soil moisture was observed on July and August while the maximum was on May and June at all types of sites. In addition, the amplitude of soil moisture variation decreased in the order of harden sand>flat sand>clay>longitudinal dune that may result from the use of periodic irrigation system.

Table 2 summarizes the soil water storage as well as the soil water deficit during a one-year experimental period. In comparison with the results of control group, the soil water storage decreased after the growing season at all types of site. Specifically, the soil water storage of the longitudinal dune deceased 3.7 mm, the harden sand 7.8 mm, the flat sand 2.6 mm, and the clay 7.3 mm. A preliminary explanation, based on the current irrigation system, is that the total water amount of plant consumption together with the water evaporation is close to that of irrigation each year. In addition, the soil water storage showed a linear relationship with the planting year, given by $y = -49.47t+450.85$ (R^2=0.8398), where y is

Table 1 Soil hydrology effect changes at different planting years (soil depth 360 cm)

	Ten years			Seven years			Four years			One year		
	V_s	WC	DWC	V_s	WC	DWC	V_s	WC	DWC	V_s	WC	DWC
May	0.076	300	1078	0.083	274	1104	0.090	323	1056	0.127	457	921
June	0.079	275	1104	0.076	284	1094	0.090	323	1056	0.118	427	952
July	0.082	276	1102	0.077	294	1085	0.087	314	1065	0.114	410	969
August	0.078	277	1102	0.077	281	1097	0.087	312	1067	0.111	400	978
September	0.084	281	1097	0.088	301	1078	0.092	331	1048	0.122	441	938
October	0.085	288	1090	0.080	307	1072	0.090	326	1053	0.127	458	920

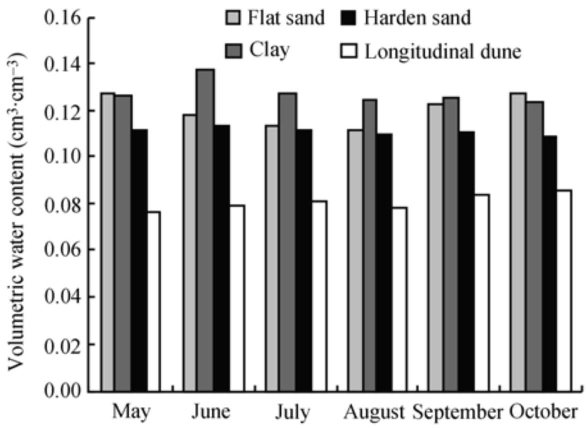

Figure 5 The dynamics of soil moisture with different site types.

soil water storage (mm) and *t* is the planting year.

3 Conclusions and discussions

The water is one of the most important factors for desert vegetation. The variation of soil moisture is key information required for the ecological restoration of desert and the sustainability of vegetation reconstruction project[26]. The soil water content as well as the variation of soil moisture can be affected by plant growth and the seasonal variation. An understanding about the dynamics of soil moisture variation is very important for constructing and maintaining the desert vegetation and the improving the water utilization[27]. The study of the temporal variation of soil moisture in shelterbelts along the Tarim Desert Highway within irrigation interval reveals that there exists a linear relationship between the soil water storage and the number of days after the irrigation. In addition, the study of soil moisture in the direction perpendicular to the horizon indicates that the soil moisture varies drastically within the soil depth of 80 cm while changes little below a soil depth of 100 cm. Moreover, the soil profile can be divided into 4 layers from the top of soil, i.e., the quickly changing layer, the active layer, the weakly layer and the regulated layer, which is different from that of Feng et al.[28]. Particularly, it was found that the soil moisture in the weakly layer was greatly affected by the diffusion and distribution of soil moisture. As a result, the soil moisture varies greatly.

Both the soil moisture and soil water storage decrease with the number of planting year, while the soil water deficit greatly increases. Moreover, there is a significant correlation between the soil water storage and the number of planting year. Based on the current irrigation system, an average soil moisture, above 6%, in shelterbelts along the Tarim Desert Highway can meet the requirement for plant growth.

The monthly change of soil moisture varies little at different types of sites in the whole growing season in shelterbelts along the Tarim Desert Highway. But, the change in the soil water storage in harden sand was the highest among all types of sites. This conclusion was further verified by the conventional guidelines of the shelterbelts engineering design: both the harden sand and lowland of ridge should be planted by deep root desert vegetation, such as *Tamarix* and *Haloxylon*. In addition, the combination of deep root desert vegetation and shallow-root plants can make full use of the soil moisture at different soil depths and promote the water diffusion to supply soil moisture to the depth of soil in the soil moisture cyclic process[29].

However, because of the special environmental conditions, even though the shelterbelts with a high planting density throughout the Tarim Desert Highway can effectively prevent the highway from the wind damage and fix sands, the increase in the minimum water consumption with the increase of planting density of shelterbelts creates a challenge for water management. Therefore, our study can provide some useful information required for formulating a better scientific water-saving irrigation scheme. Moreover, a study about the effects of plants

Table 2 Soil hydrology effect changes at different site types (soil depth: 360 cm)

Item	Site types	May	June	July	August	September	October	Average
WC (mm)	Longitudinal dune	274.3	284.0	293.8	281.4	300.9	270.6	290.2
	Harden sand	453.8	495.8	460.8	448.1	450.5	446.0	459.2
	Clay	400.6	409.9	400.6	396.5	398.3	393.3	399.9
	Flat sand	325.5	322.7	313.6	311.9	330.8	322.9	321.2
DWC (mm)	Longitudinal dune	1282.6	1272.9	1263.1	1275.6	1256.0	1250.4	1266.8
	Harden sand	1083.7	1041.7	1076.7	1089.4	1086.9	1091.5	1078.3
	Clay	903.3	894.0	903.3	907.5	905.6	910.6	904.0
	Flat sand	1055.7	1055.8	1065.0	1066.6	1047.7	1053.0	1057.3

under drought stress and soil water deficit at the deeper soil profile will have practical significance.

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