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Short Communication

Grading Woodland Soil Water Productivity and Soil Bioavailability in the Semi-Arid Loess Plateau of China

In the semi-arid region of the Loess Plateau in China, a portable photosynthesis system (Li-6400) and a portable steady porometer (Li-1600) were used to study the quantitative relation between the soil water content (SWC) and trees' physiological parameters including net photosynthesis rate (P_n), carboxylation efficiency (CE), transpiration rate (T_r), water use efficiency of leaf (WUE_L), stomatic conductivity (G_s), stomatal resistance (R_s), intercellular CO_2 (C_i), and stomatal limitation (L_s). These are criteria for grading and evaluating soil water productivity and availability in forests of Black Locust (*Robinia pseudoacacia*) and Oriental Arborvitae (*Platycladus orientalis*). The results indicated: To the photosynthesis of Locust and Arborvitae, the SWC of less than 4.5 and 4.0% (relative water content (RWC) 21.5 and 19.0%) belong to ''non-productivity and non-efficiency water''; the SWC of 4.5–10.0% (RWC 21.5–47.5%) and 4.0–8.5% (RWC 19.0–40.5%) belong to ''low productivity and low efficiency water''; the SWC of 10.0–13.5% (RWC 47.5–64.0%) and 8.5–11.0% (RWC 40.5–52.0%) belong to ''middle productivity and high efficiency water''; the SWC of 13.5–17.0% (RWC 64.0–81.0%) and 11.0–16.0% (RWC 52.0–76.0%) belong to ''high productivity and middle efficiency water''; the SWC of 17.0–19.0% (RWC 81.0–90.5%) and 16.0–19.0% (RWC 76.0–90.5%) belong to ''middle productivity and low efficiency water''; the SWC of more than 19.0% (RWC 90.5%) belongs to ''low productivity and low efficiency water''. The SWC of about 13.5 and 11.0% (RWC 64.0 and 52.0%) are called ''high productivity and high efficiency water'', which provides the further evidence for Locust and Arborvitae to get both higher productivity (P_n and CE) and the highest WUE_L and adaptation to the local environment, respectively.

Keywords: *Platycladus orientalis*; *Robinia pseudoacacia*; Semi-arid region; Soil quality; Water use efficiency

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1 Introduction

The ultimate aim of forest establishment in the semi-arid region of Loess Plateau is to form forest ecosystem that can use the insufficient rainfall with higher efficiency. It is one of the important theoretical and technological issues on how to enhance soil water use efficiency [1–3]. However, limited by the randomness of rainfall and difficulty in soil moisture control, few studies were carried out on the relation between tree growth and soil moisture [4–6], especially on the impacts of different soil water contents (SWC) on water availability, tree growth, and water use efficiency [7] under different SWC.

Soil moisture availability is studied actively in the field of agriculture [8–10], its classical concept is generalized as both equivalent availability [11] and non-equivalent availability [12]. In the near future, with development of SPAC (soil–plant–atmosphere continuum) theory and progress in test techniques of soil moisture movement [13, 14], soil moisture availability is studied using kinetic models of soil moisture absorption by plant roots [15–17]. However, the conclusions differ from each other because of difference in study methods and evaluation standards. Virtually, soil moisture availability is connected with soil properties, plant growth status, and weather condition.

So far, the soil moisture availability in woodland is only qualitatively described using the concept of soil water constants (such as soil capacity and wilting point) [18, 19], but lack of studies on quantitative relation between trees growth and soil moisture.

The paper studied the quantitative relation between some photosynthetic physiological parameters and soil moisture, established the criteria for grading and evaluation of soil moisture availability

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Abbreviations: **CE**, carboxylation efficiency; C_i, intercellular CO_2; G_s, stomatic conductivity; L_s, stomatal limitation; P_n, photosynthesis rate; R_s, stomatal resistance; **RWC**, relative water content; **SWC**, soil water content; T_r, transpiration rate; WUE_L, water use efficiency of leaf

The authors contributed equally: J. B. Xia and G. C. Zhang and productivity of Black Locust (*Robinia pseudoacacia*) and Oriental Arborvitae (*Platycladus orientalis*) forests. That will certainly serve as guidance in constructing the forest ecosystem with water-saving and high efficiency in the semi-arid Loess Plateau.

2 Materials and methods

2.1 Experimental site

The experimental site is located in the ''Runoff Forestry Experimental Station'' of Beijing Forestry University, and belongs to the Tugouqiao small watershed in Fangshan County, Shanxi Province. It lies at North latitude 37°36′58″, East longitude 110°02′55″, with an average altitude of about 1200 m and the maximum of 1446 m, with dryness index of 1.3. Average annual precipitation is 416.0 mm and the precipitation in July–September accounts for over 70%. Annual potential evaporation is 1857.7 mm and the biggest evaporation appears in April–June, representing the typical character of severe spring drought in semi-arid region in the north of China. The experimental site belongs to typical landform of Loess Hilly and Gully Region; the soil texture is uniform, belonging to medium soil, and loessal soil.

2.2 Experimental materials

The experimental materials are Black Locust (*R. pseudoacacia*) forest at the age of 9 years old, Oriental Arborvitae (*P. orientalis*) forest at the age of 14 years old, and their 4 years old nursery stocks potted (20 plants every tree species). The soil water stress grads were applied by artificial water supply. Average soil bulk density is 1.20 g cm^{-3}, and average field capacity is 21.0% or so.

2.3 Experimental observation methods

Transpiration and photosynthesis were observed by the portable steady porometer (Li-1600) and portable photosynthesis system (Li-6200), respectively. The stands of Black Locust and Oriental Arborvitae were observed to the leaves on the middle and upper section of the tree crown in the south and north, respectively; the potted nursery stocks were observed, respectively, to the leaves on the upper, middle, and lower part of the crown. Every observation repeats three times. The observation began at 24–36 h after artificial water supply every time and the transpiration and photosynthesis were observed at the same time. Because transpiration rate (T_r) determined by the steady porometer (Li-1600) was higher than the T_r under natural condition, and the higher the SWC was, the bigger the error would be. The T_r was moderately revised with speedy weight method [17, 20]. The observations were conducted in May–September of 2000 and the duration was at 9:00–11:00 am on sunny day every time.

The measurement of soil moisture was carried out on the same day as observation of tree physiological parameters. The SWC of woodland was measured by LNW-50A neutron probe method, the depth of observation is 100 cm (a layer every other 20 cm); SWC of potted trees was measured by gravimetric sampling method. In this paper, the SWC is mass water content, relative water content (signed by RWC) is the ratio of SWC to field capacity.

3 Results

The quantitative relations between soil water and the following physiological parameters were, respectively, measured: (1) Net photosynthesis rate (P_n: μmol CO_2 m^{-2} s^{-1}); (2) carboxylation efficiency (CE: mol CO_2 m^{-2} s^{-1}); (3) T_r (mmol H_2O m^{-2} s^{-1}); (4) water use efficiency of leaf (WUE_L: μmol CO_2 mmol H_2O^{-1}); (5) stomatic conductivity (G_s: cm s^{-1}); (6) stomatal resistance (R_s: s cm^{-1}); (7) intercellular CO_2 concentration (C_i: μL CO_2 L^{-1}); (8) stomatal limitation (L_s: %). The mathematic models of the first four parameters are shown in Tab. 1.

3.1 Relation of photosynthetic physiological parameters and soil moisture

3.1.1 Response of P_n and CE to soil water content (SWC)

As shown in Table 1, Eqs. (A) and (B) and (E) and (F), and Fig. 1a and b, the response curves of net P_n and CE to SWC conform to a quadratic equation.

By calculating the extremal value [17] of Eqs. (A) and (E), two SWC critical values of soil water availability to P_n (signed by and $SWC_{P_{n=0}}$) were ascertained, respectively, $SWC_{P_{n=max}}$ corresponding to the maximum P_n and $SWC_{P_{n=0}}$ resulting in P_n up to naught (called soil hydration compensation point). The $SWC_{P_{n=max}}$ of Black Locust and Oriental Arborvitae was, respectively, 17.13% (about 17.0%) and 16.0% (RWC was about 81.0 and 76.0% in turn); the $SWC_{P_{n=0}}$ of two tree species was, respectively 4.55 and 3.91% (about 4.5 and 4.0%; RWC about 21.0 and 19.0%). Similarly, by calculating the extremal value of Eqs. (B) and (F), two SWC critical values of soil water availability to CE (signed by $SWC_{CE=max}$ and $SWC_{CE=0}$) were ascertained, respectively, $SWC_{CE=max}$ maintaining the maximum CE and $SWC_{CE=0}$ resulting in CE up to naught. The $SWC_{CE=max}$ of Locust and Arborvitae was 15.7 and 16.25% (about 16.0%; RWC about 76.0%), respectively; the $SWC_{CE=0}$ of two tree species was 3.8 and 3.6%, respectively. That is to say, the SWC 17.0 and 16.0% (RWC about 81.0and 76.0%) had, respectively, the highest availability to photosynthesis of Locust and Arborvitae; the SWC of less than 4.5 and 4.0% (RWC about 21.0 and 19.0%) was non-available in turn.

Table 1. Regression models on relation of physiological parameters and SWC (θ: %)

Tree species	Parameter ~ SWC (θ)	Regression model	Rsq.	df	F
Black Locust	$P_n \sim \theta$ (A)	$P_n = -13.3360 + 3.3818\,\theta - 0.0987\,\theta^2$	0.903	33	153.2
	$CE \sim \theta$ (B)	$CE = -0.0673 + 0.01570\,\theta + 0.0005\,\theta^2$	0.850	33	93.5
	$T_r \sim \theta$ (C)	$T_r = -0.1769 + 0.2735\,\theta + 0.0492\,\theta^2 - 0.0020\,\theta^3$	0.775	32	36.6
	$WUE_l \sim \theta$ (D)	$WUE_l = -3.4148 + 1.096\,\theta - 0.0692\,\theta^2 + 0.0014\,\theta^3$	0.812	32	46.2
Oriental Arborvitae	$P_n \sim \theta$ (E)	$P_n = -5.7340 + 1.6701\,\theta - 0.0522\,\theta^2$	0.924	40	259.1
	$CE \sim \theta$ (F)	$CE = -0.0228 + 0.0065\,\theta + 0.0002\,\theta^2$	0.892	40	187.3
	$T_r \sim \theta$ (G)	$T_r = 1.6161 - 0.4123\,\theta + 0.0735\,\theta^2 - 0.0022\,\theta^3$	0.923	39	172.1
	$WUE_l \sim \theta$ (H)	$WUE_l = -3.4361 + 1.3062\,\theta - 0.094\,\theta^2 + 0.0021\,\theta^3$	0.908	39	65.7

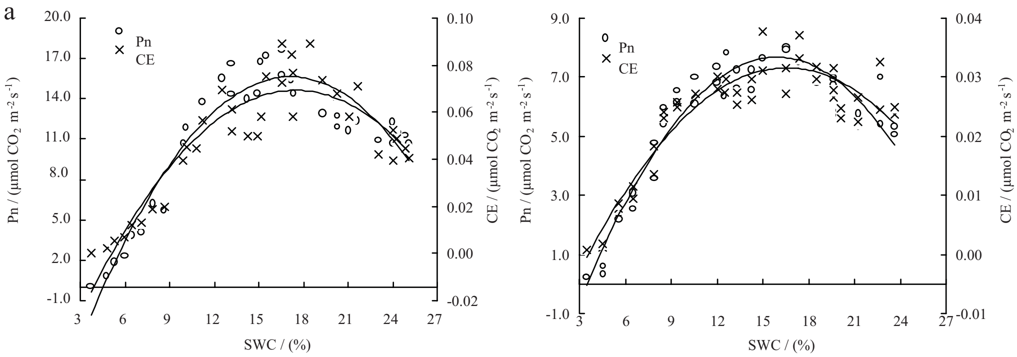

Figure 1. Response curves of P_n and CE to SWC: (a) Locust and (b) Arborvitae.

3.1.2 Response of T_r and WUE_L to SWC

Relations of T_r, WUE_L, and SWC were shown in Fig. 2a and b and Tab. 1, Eqs. (C) and (D) and (G) and (H).

The results indicate that response curves of T_r and WUE_L of Locust and Arborvitae to SWC conform to cubic equation. By calculating the extremal value [17, 21] of Eqs. (C) and (D) and (G) and (H), both $SWC_{Tr=max}$ and $SWC_{WUE_L=max}$ are ascertained, $SWC_{Tr=max}$ and $SWC_{WUE_L=max}$ are the SWC critical values, respectively, to support the maximum T_r and WUE_L; the $SWC_{Tr=max}$ of Black Locust and Oriental Arborvitae was 18.82 and 18.98% (about 19.0%; RWC about 90.5%), the $SWC_{WUE_L=max}$ of two tree species was 13.23 and 11.01% (about 13.5 and 11.0%, RWC about 64.0 and 52.0%) in turn, namely SWC 13.5 and 11.0% had, respectively, the highest availability to WUE_L of Black Locust and Oriental Arborvitae; SWC 19.0% had the highest availability to T_r of two tree species.

3.1.3 Response of G_s, R_s, L_s, and C_i to SWC

The response curves of stomatal conductance (G_s), R_s, L_s, and C_i to SWC were shown in Fig. 3a–d.

As shown in Fig. 3a–d, when SWC was below $SWC_{P_n=max}$ (Locust and Arborvitae were 17.0 and 16.0%, respectively), the L_s-SWC curves and C_i-SWC curves of Locust and Arborvitae had obvious turning points corresponding to SWC 10.0 and 8.5%, respectively (signed by $SWC_{SL \to nSL}$, meaning that the SWC critical value to result in photosynthesis decreased from L_s to non-L_s). From $SWC_{P_n=max}$ to $SWC_{SL \to nSL}$, P_n, and G_s decline (R_s increase), but L_s increased and C_i decreased with the decline of SWC (see Fig. 3c and d), which shows that P_n decline was largely due to L_s by the theory of plant physio-ecology [12, 18], i.e., CO_2 supply was limited as a result of G_s decrease (R_s increase); however, in SWC of below $SWC_{SL \to nSL}$, P_n and G_s decline (R_s increase), but L_s decrease and C_i increase remarkably with the decline of SWC (see Fig. 3c and d), that indicates that P_n decline was largely caused by non-L_s [8, 10, 12], i.e., mesophyll cells photosynthetic capacity decreased because of heavy water stress. Therefore, SWC 10.0 and 8.5% (RWC 47.5 and 40.5%) are regarded as respective soil water critical value to result in Locust and Arborvitae photosynthesis decrease from L_s to non-L_s ($SWC_{SL \to nSL}$).

After water stress, plant leaf photosynthesis decline undergo generally a course from L_s to non-L_s, once photosynthesis suffer the non-L_s, photosynthetic organization and chloroplast have been damaged by heavy water deficit [13, 14], if SWC decreases further, plant photosynthetic productivity will be badly reduced because of leaves wilting. So that SWC 10.0 and 8.5% (RWC 47.5 and 40.5%) was ascertained as lower limit value of soil moisture with higher availability to Locust and Arborvitae respective photosynthesis.

3.2 Grading and evaluation of soil water availability and productivity

From the analysis in Section 3.1, some SWC critical values have been found with the highest or lowest availability to each photosynthetic physiological parameter of Black Locust and Oriental Arborvitae (Tab. 2). According to the results, soil water availability was divided into different range, and criteria for grading and evaluation of

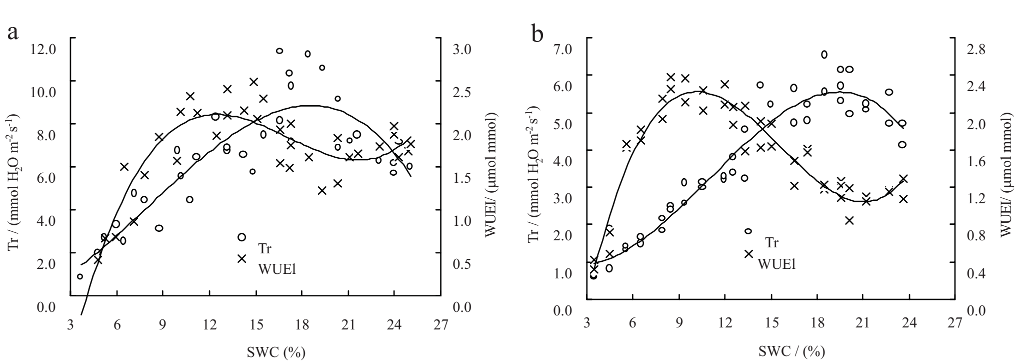

Figure 2. Response of T_r and WUE to SWC: (a) Locust and (b) Arborvitae.

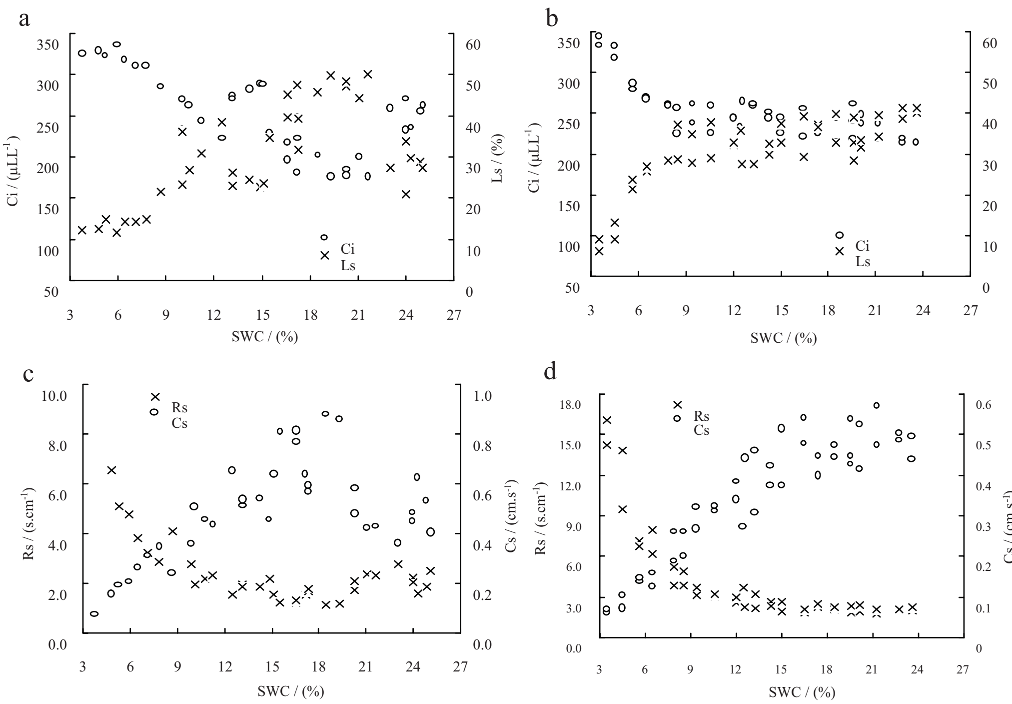

Figure 3. Response of C_i, L_s, R_s, and C_s to SWC: (a and c) Locust and (b and d) Arborvitae.

Table 2. SWC critical value of soil water availability to trees physiological parameters

Tree species	The SWC (%) critical value					
	$SWC_{P_{n=0}}$	$SWC_{SL \rightarrow nSL}$	$SWC_{WUE_{L=max}}$	$SWC_{CE=max}$	$SWC_{P_{n=max}}$	$SWC_{Tr=max}$
Black Locust	4.5	10.0	13.5	16.0	17.0	19.0
Oriental Arborvitae	4.0	8.5	11.0	16.0	16.0	19.0

woodland soil water productivity and availability were set up (Tab. 3).

These grading criteria were built on the theory of plant water physiology, each SWC critical value ascertained in Tabs. 2 and 3 was based entirely on the quantitative relation between trees' physiological parameters and soil moisture; new concepts were used, such as ''productivity (P_n and CE)'' and ''efficiency (WUE_L)'' instead of conventional concept of ''availability'', ''soil hydration compensation point ($SWC_{P_{n=0}}$)'' instead of classical concept of ''soil wilting point'', so each new concept was definitely provided with plant physiological significance. For example, ''high productivity'' and ''high efficiency'' mean high P_n, CE, and WUE_L; ''middle productivity'' and ''middle efficiency'' mean middle or middle upwards P_n, CE, and WUE_L.

Table 3. Grading criterion of soil water productivity and bioavailability

Grading of soil water productivity and availability	Range of soil moisture			
	Relative water content (RWC; %)		Soil water content (SWC; %)	
	Black Locust	Oriental Arborvitae	Black Locust	Oriental Arborvitae
Non-productivity and non-efficiency water	<21.5	<19.0	<4.5	<4.0
Low productivity and low efficiency water	21.5–47.5	19.0–40.5	4.5–10.0	4.0–8.5
Middle productivity and high efficiency water	47.5–64.0	40.5–52.0	10.0–13.5[a)]	8.5–11.0[a)]
High productivity and middle efficiency water	64.0–81.0	52.0–76.0	13.5[a)]–17.0	11.0[a)]–16.0
Middle productivity and low efficiency water	81.0–90.5	76.0–90.5	17.0–19.0	16.0–19.0
Low productivity and low efficiency water	>90.5	>90.5	>19.0	>19.0

[a)] Note: The optimum soil water content (SWC is 13.5 and 11.0%, respectively), of Black Locust and Oriental Arborvitae, called ''water of high productivity and high efficiency''.

In the range of ''low productivity and low efficiency water'', both P_n and WUE_L were very low and decreased rapidly with the decrease (or increase) of SWC, i.e., soil water availability to P_n and WUE_L decreased quickly. In the range of ''middle productivity and high efficiency water'', WUE_L was at the highest level all along, i.e., soil water had coequal availability to WUE_L; P_n and CE were higher but declined with the decrease of SWC, i.e., soil water availability to P_n and CE decreased. In the range of ''high productivity and middle efficiency water'', P_n was at the highest level all along, i.e., soil water had coequal availability to P_n; WUE_L was higher but declined with the decrease of SWC, i.e., soil water availability to WUE_L decreased. In the range of ''middle productivity and low efficiency water'', both P_n and CE were higher but WUE_L was lower, and all of them decreased with increase of SWC, in other words, soil water availability to P_n, CE, and WUE_L declined.

The core of vegetation construction is to enhance water use efficiency effectively, rather than to obtain the highest yield by enough water supply, because of aridity and shortage of water resources, especially insufficient rainfall in the semi-arid Loess Plateau [1, 20, 21]. So the ''middle productivity and high efficiency water'' should be selected as criterion to control woodland soil moisture, in this soil moisture range, the higher SWC was, the higher water productivity and water use efficiency were; there into, the optimal SWC was about 13.5 and 11.0% (RWC 64.0 and 52.0%), respectively, on the woodland of Black Locust and Oriental Arborvitae, which support trees to obtain both higher productivity and water use efficiency, known as the ''high productivity and high efficiency water''.

4 Discussion and conclusions

With the highest availability to P_n of Locust and Arborvitae, the SWC critical value was about 17.0 and16.0% (RWC 81.0 and 76.0%), respectively; SWC of below 4.5 and 4.0% (RWC 21.0 and 19.0%) was non-available water to photosynthesis of Locust and Arborvitae in turn.

The critical value of SWC resulting in P_n decrease of Locust and Arborvitae and transition from L_s to non-L_s was 10.0 and 8.5% (RWC 47.5 and 40.5%), respectively, which was also the lower limit value of soil moisture for higher availability to photosynthesis of Locust and Arborvitae, respectively.

With the highest availability to WUE_L of Locust and Arborvitae, the SWC critical value was, 13.5 and 11.0% (RWC 64.0 and 52.0%), respectively; with the highest availability to T_r of two tree species, the SWC critical value was 19.0% (RWC 90.5%).

On Locust and Arborvitae woodland, the SWC of less then 4.5 and 4.0% (RWC 21.5 and 19.0%) belong to ''non-productivity and non-efficiency water''; the SWC of 4.5–10.0% (RWC 21.5–47.5%) and 4.0–8.5% (RWC 19.0–40.5%) belong to ''low productivity and low efficiency water''; the SWC of 10.0–13.5% (RWC 47.5–64.0%) and 8.5–11.0% (RWC 40.5–52.0%) belong to ''middle productivity and high efficiency water''; the SWC of 13.5–17.0% (RWC 64.0–81.0%) and 11.0–16.0% (RWC 52.0–76.0%) belong in ''high productivity and middle efficiency water''; the SWC of 17.0–19.0 (RWC 81.0–90.5%) and 16.0–19.0% (RWC 76.0–90.5%) belong to ''middle productivity and low efficiency water''; the SWC of more than 19.0% (RWC 90.5%) belong also to ''low productivity and low efficiency water''.

On woodland of Black Locust and Oriental Arborvitae, the optimal SWC was 13.5 and 11.0% (RWC 64.0 and 52.0%), respectively, or so, which are called ''high productivity and high efficiency water'' because of supporting trees to obtain both higher water productivity and the highest water use efficiency, in the semi-arid Loess Plateau.

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