Response of Coarse Root Distribution of Populus euphratica Oliv. to Soil Moisture in Extreme Arid Region China

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Response of Coarse Root Distribution of *Populus euphratica* Oliv. to Soil Moisture in Extreme Arid Region China

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Abstract

Generally root systems of tree are divided into coarse root system and fine root system. As well as fine root system, coarse root system is important to well growth of tree too. Based on the data observed at Ejina Banner Inner Mongolia Autonomous Region, China from May to July of 2006, using fractal theory and statistical method, the relationship between coarse root system distribution of *Populus euphratica* Oliv. and soil moisture in root zone was analyzed. Root system of tree has a typical fractal characteristic. For a fractal system, its exterior form is complex, while the fractal dimension (D) is a constant. So we computed D of coarse root system and mean soil moisture (E) in root zone of each sample tree, got a function between D and E. This function shows how does the coarse root system of *Populus euphratica* Oliv. change in different soil moisture in root zone. So we can judge coarse root distribution of *Populus euphratica* Oliv. by the function. If E is less than 11.02%, then root fractal dimensions increase with E; if E is more than 11.02%, root fractal dimensions decrease with E. Based on the function, we got an interval of E, (5%, 24.5%), in which *Populus euphratica* Oliv. grows more well.

Keywords : extreme arid region, *Populus euphratica* Oliv., root distribution, soil moisture, root fractal dimension

1 INTRODUCTION

The ability of plants to use different sources depends on their root systems (Squeo *et al*., 2006). Root system can be regarded as the result of the accumulated effects of growth and branching responses by individual root tips and the root tissue behind these root tips to local soil conditions and the overall state of the plant. Root growth characteristics change in response to local soil patterns feed back on the soil characteristics through changes in uptake (Diggle, 1988). Quantification of roots distribution also contributes to an improved understanding of chemical fluxes in the vadose zone in both ecological and hydrological studies (Somma *et al*., 1998), as well as their control by vegetation. Since 1970 there are many studies related to root

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studies focus on crop root systems. In recent years, some studies began to pay more attention to the root systems of tree (Katul *et al.*, 1997; Green *et al.*, 1997; Vrugt *et al*., 2001; Zhu *et al*., 2001; Zhang *et al*., 2004; Gong *et al.*, 2006). For tree, root systems are generally divided into fine root system (root diameter is less than 2 mm) and coarse root system (root diameter is more than 2 mm) (Green et al., 1999). Compared with the research of fine root system of tree, the research on the coarse root system of tree is especially rare (Diggle, 1988; Pages *et al*., 1989; Coelho *et al*, 1999; Vercam bre *et al.*, 2003). In fact, coarse root system is also very important to well growth of tree. In this study, choosing *Populus euphratica* Oliv. in Northwest of China as research object, we investigate the distribution of coarse root system of tree in extreme arid region, in the hope that valuable reference and theory foundation on the research of the law of root uptake water and the influence of arid environment can be supplied.

Populus euphratica Oliv. is a tree growing naturally in arid desert oases. Most *P. euphratica* Oliv. trees grow in China, Iran, Iraq, Syria, Turkey, Pakistan, Spain and Central Asia countries. The area of *P. euphratica* Oliv. Forest in China occupies 61% in the world. *P. euphratica* Oliv. trees can endure saline and humid environment, moreover it can resist aridity and windstorm. So *P. euphratica* Oliv. forest favors the balance of the ecosystem in arid desert oases, protects dweller and the production of agriculture-stockbreeding. However, because of global warming, population growth , human damage and so on, *P. euphratica* Oliv. forest has deteriorated in the world since the mid-20th century. Many resuming measures have been adopted, whereas the effect is not good. So it is important to study the root systems distribution of *P. euphratica* Oliv. forest for both breeding *P. euphratica* Oliv. forest and helping to better manage irrigation system. Due to desert soil in an arid environment has low and limited water contents, in which soil water availability is the prime factor limiting the number and size of perennial plant species and thus is the main constraint in permanently controlling (Hadley *et al* ., 1981; Berndtsson and Chen, 1994; Berndtsson *et al*., 1996; Southgate et al., 1996; Li *et al*., 2004). It is necessary to investigate the relationship between roots distribution of *P. euphratica* Oliv. and soil moisture.

Many phenomena in nature, such as physiognomy evolution of basin, morphology of geological disaster, have fractal characteristic. Fractal theory provides a new way to study these complex phenomena (Sulitan *et al*., 2004; Li, 2005, Li, *et al* ., 2006). The root systems of plant have typical fractal characteristic, so we compute fractal dimension of coarse root system of *P. euphratica* Oliv., and farther the nonlinear relationship between fractal dimension of coarse root system and soil moisture is analyzed in this paper.

2 MATERIALS AND METHODS

Experimental site and plant material

The experiment is conducted at Erdao Bridge Protected Area of *Populus euphratica* Oliv. forest in Ejina Banner, Inner Mongolia Autonomous Region, China (see Figure 1), over eight-weeks period (18 May to 12 July, 2006). Ejina drainage basin, an arid desert oasis, is one of main areas of *P. euphratica* Oliv. forest in China. This region is one of the driest areas in China, in which mean annual precipitation is only 42 mm, while mean annual evaporation is 3755 mm. In the Protected Area of *P. euphratica* Oliv., the shade density of *P. euphratica* Oliv. forest is 0.8, and the population density is 500 trees ha^{-1}. Most *P. euphratica* Oliv. trees are young and adult. The region's soil type is a poplar soil, varying from aclay loam to sand. Organic matter content is 0.72 % in the 0-30 cm soil layer and 0.13% in the 30-200 cm soil layer. Ground water levels ranges from 1.5-3.5 m in depth. The understory includes the species *Sophora alopecuroides* Linn. and *Tamarix*

Table 1 DBH of each 20 sample trees

Sample tree	No. 1	No. 2	No. 3	No. 4	No. 5	No.6	No.7	No. 8	No. 9	No. 10
DBH(cm)	16	14	11	13	10	11	12	13	12	11
Sample tree	No. 11	No. 12	No. 13	No. 14	No. 15	No. 16	No. 17	No. 18	No. 19	No. 20
DBH(cm)	12	10	13	13	12	14	15	13	15	15

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200 *P. euphratica* Oliv. trees in the Protected Area are sampled at random, and which DBH (diameter at breast height) is measured. By the frequency of DBH, we consider that the distribution of DBH of *P. euphratica* Oliv. nearly obey normal distribution, and mean value of DBH is 12.65 cm, standard deviation is 2.2 cm (see Figure 2.). Among them we select independently and randomly 20 *P. euphratica* Oliv. trees and numbered them from 1 to 20, which DBH are between 10 cm and 16 cm (see Table 1.). There are no

Observation of the root system

Root excavation is conducted from May 18 to July 10, 2006. In order to observe the size and direction of the coarse root system, excavation is done around the tree firstly, which radius is approximately 2 m, and its depth is 1.5 m. Secondly, a section is excavated along the direction of coarse root system (i.e. main roots direction), which is 6 m long, and 1.5 m wide and 1.5 m deep (see Figure 3 (a)).

Measurements of soil moisture

Soil moisture is measured using a TRIME-FM time domain reflectometry (TDR) tube probe in five glass fiber tubes, which are 100 cm, 200 cm, 300 cm, 400 cm and 500 cm away from the tree trunk along the main roots direction in horizontal radial. Access tubes of 120cm length were installed for the TRIME-FM TDR tube probe at positions as shown in Figure 3 (b). The vertical profile of soil moisture in every tube was determined from measurements of soil moisture at 20 cm intervals. Ditto for all 20 sample trees.

On the other hand, owing to the maximum and minimum value of soil moisture in root zone are very useful in studying the relationship between roots distribution and soil moisture in root zone, data of soil moisture during five years (from 2001 to 2005) of the experiment site are showed (see Table 2.).

Data procession method

To study the relationship between roots distribution and soil moisture in root zone, quantitative analysis of them should be conducted. For a fractal system, the exterior form is complex, while the fractal dimension is a constant (Falconer, 1990). Roots distribution of tree has a typical fractal characteristic, thus, the root fractal dimension should depict the characteristic of roots distribution. In order to compute the root fractal dimension of each sample tree, coarse root system is classified into four types: root diameter is between 0.2-2 cm, 2-5 cm, 5-8 cm and >8 cm. Amount of roots under different types are recorded. Ditto for all 20 sample trees. According to fractal theory, if

$$CF \propto RD^{-D} \quad (1)$$

then D is fractal dimension of root districution.

where RD is root diameter, CF is cumulative frequency of root amount in corresponding root diameter.

That is, $$D = -\frac{\ln(CF)}{\ln(RD)} \quad (2)$$

Table 2. Soil moisture during five years of the experiment site

Soil depth (cm)	Soil moisture ($cm^3 \cdot cm^{-3}$) Mini. value	Max. value	Soil depth (cm)	Soil moisture ($cm^3 \cdot cm^{-3}$) Mini. value	Max. value
20	0	29.65%	80	2.3%	34.0%
40	0	21.3%	100	7.45%	36.7%
60	1.3%	24.4%	120	6.55%	46.05%

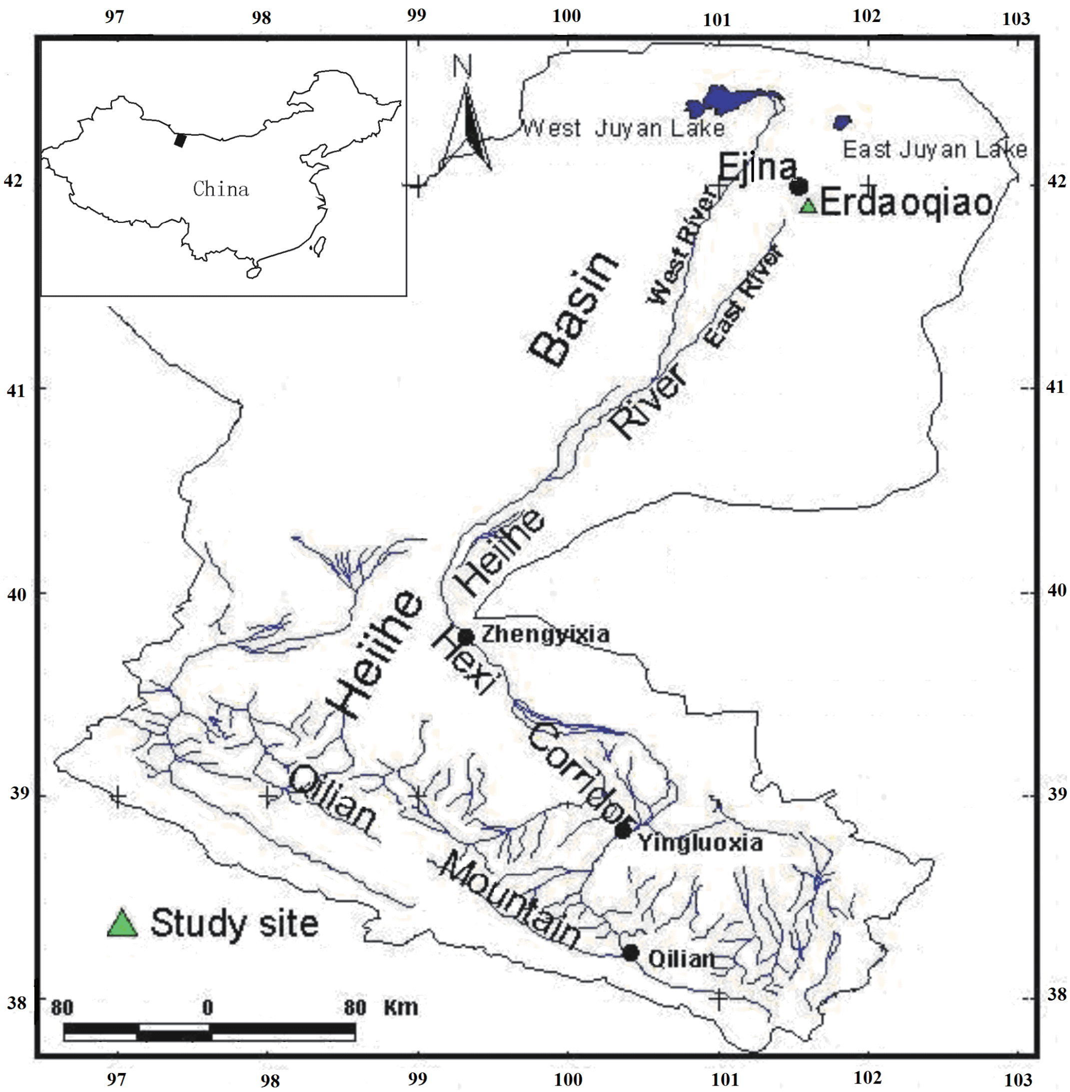

Figure 1 Location of the study area and observation site.

other *P. euphratica* Oliv. trees around every sample tree (the centre is the trunk of each trees, and radius is 600 cm), and the soil type of each tree is sandy loam mainly.

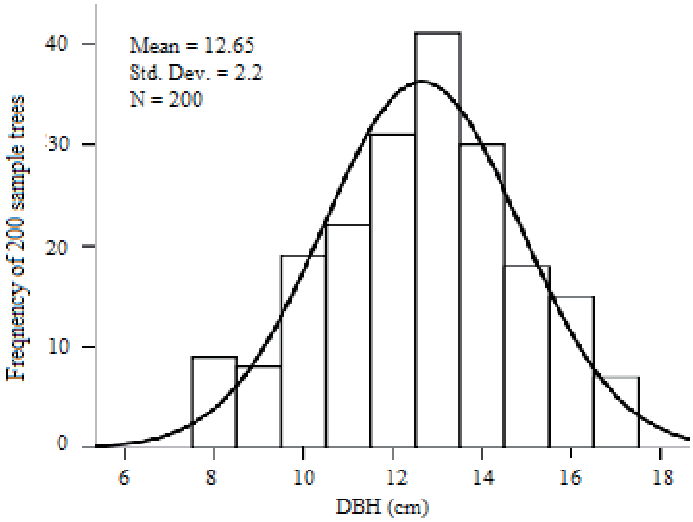

Figure 2 Frequency of DBH of 200 sample trees

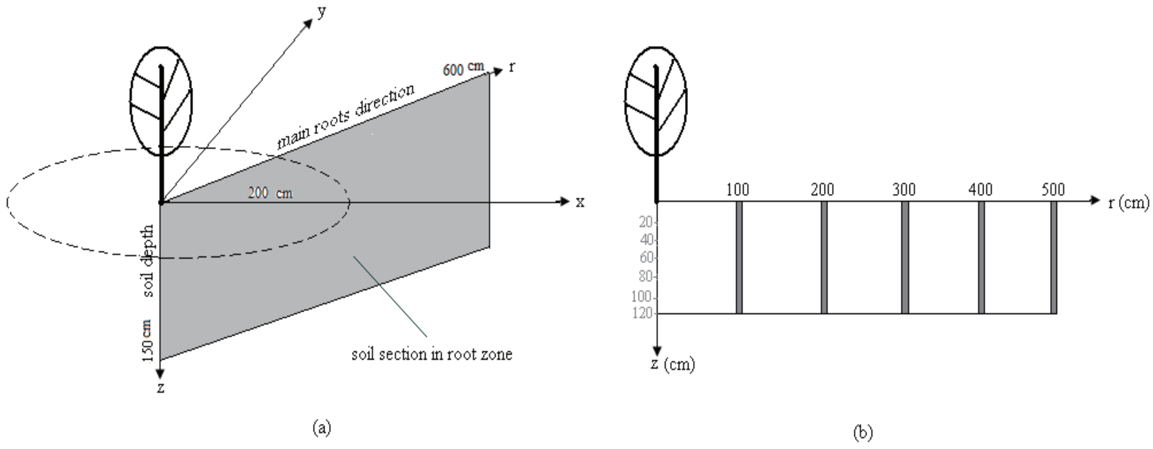

Figure 3. (a) Sketch map of excavation section of coarse root system; (b) Cross-sectional view of the distribution of TDR probes use for monitoring soil moisture.

3 RESULT AND DISCUSSION

Distribution characteristic of coarse root system

P. euphratica Oliv. trees have enormous root systems, but amount of the coarser roots which diameters excess 5cm is few, only 6.01% (see Table 3). There are developed side roots which extend all directions from 20-120 cm in depth. However, the coarser roots extend along the direction of river.

Fractal dimension of coarse root system

We computed the fractal dimension of coarse root system of each sample tree (for example, the computation of sample tree No. 1) as following. The data of sample tree No. 1 are listed in Table 4. By fractal theory, the root distribution fractal dimension of sample tree No. 1 is 1.6004. Using the method as the same above, we get the coarse root systems fractal dimensions of all the sample trees (see Table 5).

Soil moisture in root zone

Soil moisture of 20 sample trees is different, such as sample trees No. 2, No. 3, No. 11, and No. 15 (see Figure 5).

In order to explore the relationship between root fractal dimension and soil moisture in root zone, mean soil moisture of every sample tree is computed. (Table 6).

By the data from Table 4 and 5, we get the function between D and E (see Figure 6):

$D = f(E) = 5769.6E^5 - 7411.5E^4 + 3603.5E^3 - 809.22E^2 + 78.405E - 0.6247$, $R^2 = 0.80$ (4)

Table 3. Root frequency of samples in different diameters

Samples	Root frequency in different diameters				Samples	Root frequency in different diameters			
	1-2cm	2-5cm	5-8cm	>8cm		1-2cm	2-5cm	5-8cm	>8cm
No. 1	74	16	5	3	No. 11	52	2	1	1
No. 2	63	7	2	2	No. 12	10	4	1	1
No. 3	62	2	1	1	No. 13	29	2	1	1
No.4	39	4	2	1	No.14	21	2	1	1
No. 5	33	2	1	1	No. 15	76	7	2	1
No. 6	30	12	3	1	No.1 6	68	5	2	2
No. 7	86	8	2	1	No. 17	50	9	5	3
No. 8	27	6	1	1	No. 18	34	7	4	2
No. 9	9	3	2	1	No. 19	82	9	3	1
No. 10	37	4	2	1	No. 20	86	6	2	1

Table 4 Cumulative frequencies of roots in different diameter of sample tree No. 1

*RD**	>1 cm	>2 cm	>5 cm	>8 cm
CF	98	24	8	3

**RD* is ab. of root diameter; and *CF* is ab. of cumulative frequency.

Using regression analysis, we get the relationship between *RD* and *CF* (see Figure 4):

$$\ln CF = -1.6004 \ln RD + 4.4885, \quad R^2 = 0.9879 \quad (3)$$

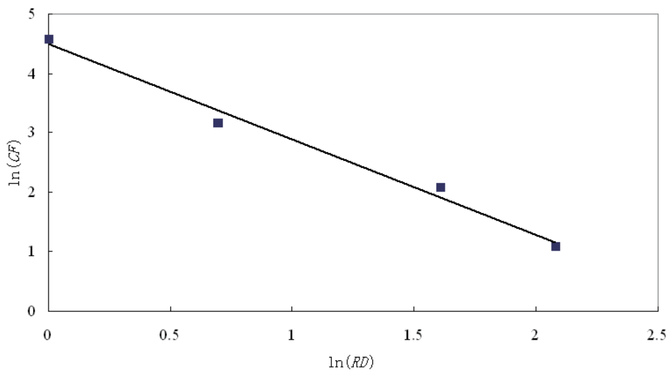

Figure 4 The relationship between *RD* and *CF* of sanple tree No. 1

Table 5. Fractal dimensions of samples (*D*)

Samples	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10
D	1.6004	1.6519	1.8469	1.5974	1.6025	1.7721	2.0861	1.6865	1.4195	1.6821
Samples	No. 11	No. 12	No. 13	No. 14	No. 15	No. 16	No. 17	No. 18	No. 19	No. 20
D	1.7775	1.5164	1.5542	1.437	2.0205	1.6376	1.3864	1.4058	2.0462	2.0506

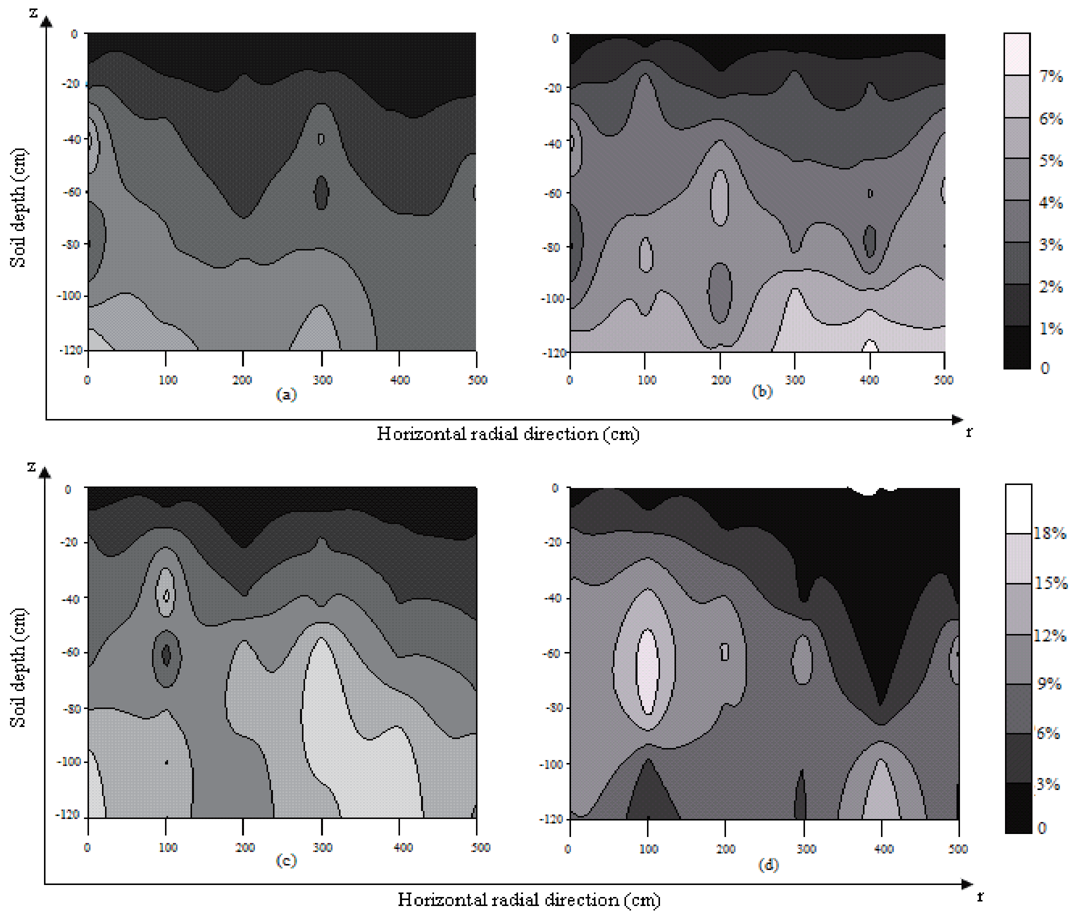

Figure 5. Soil moisture distribution of sample trees. Figure a, b, c, and d describe soil moisture distribution of sample trees No.2, 3, 11, and 15, respectively. Scales of Figure a and b are same, so do Fig. c and d.

Table 6. Mean soil moisture of each sample (*E*)

Samples	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10
E(cm^3·cm^{-3})	0.1697	0.0505	0.1644	0.1946	0.0527	0.1635	0.0889	0.1693	0.2131	0.1209
Samples	No. 11	No. 12	No. 13	No. 14	No. 15	No. 16	No. 17	No. 18	No. 19	No. 20
E(cm^3·cm^{-3})	0.153	0.0541	0.1514	0.1964	0.0427	0.06	0.2001	0.2103	0.1402	0.1304

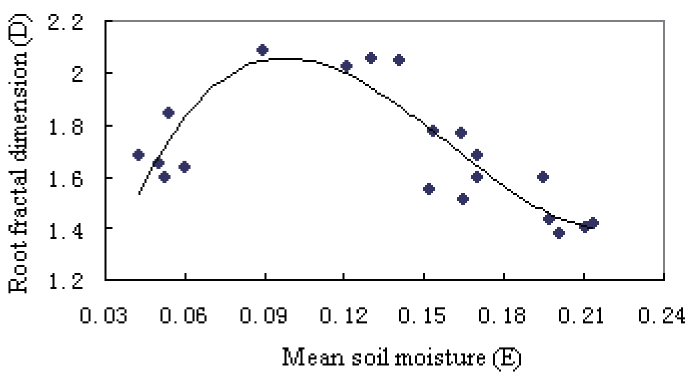

Figure6 The relationship between *D* and *E Nonlinear analysis of the relationship between D and E*

The above result shows that soil moisture in root zone affects roots distribution of *P. euphratica* Oliv. directly. The value 0.011 $cm^3 \cdot cm^{-3}$ of E is a turning point. If E is less than 0.011 $cm^3 \cdot cm^{-3}$, then D increases with E; if E is more than 0.011 $cm^3 \cdot cm^{-3}$, then D decreases with E. We know that root excavation surely does a lot of damage to root systems, especially to plant in arid region. However, by equation (4), only know soil moisture in root zone, can we deduce the distribution of coarse root system of *P. euphratica* Oliv. approximately.

The more developed root distribution is, the bigger fractal dimension is, namely, smaller fractal dimension reflects that the branch-ability of root system is lower. Thus, from Figure 6, it is know that if soil moisture is low (E< 0.011 $cm^3 \cdot cm^{-3}$), then the root's branch-ability of *P. euphratica* Oliv. increase with soil moisture; if soil moisture is high (E> 0.011 $cm^3 \cdot cm^{-3}$), then the root's branch-ability of decrease with soil moisture. That is to say, in a certain interval of E the growth of *P. euphratica* Oliv. is well.

Suitable inter val of E

In Probability theory, probability density function has a property:

$$\int_{-\infty}^{+\infty} f(x)dx = 1, \qquad (5)$$

where $f(x)$ is probability density function.

Data of soil moisture during five years (from 2001 to 2005) of the experiment site are analyzed, and the maximum and minimum value of soil moisture are ascertained, that is, E_{min}=0.031 $cm^3 \cdot cm^{-3}$ and E_{max}=0.287 $cm^3 \cdot cm^{-3}$. So the interval of E is (0.031, 0.287).

In order to determine the suitable interval of E, probability density function is used in the paper. Firstly, let

$$f^*(E) = \frac{f(E)}{\int_{0.031}^{0.287} f(E)dE} \qquad (6)$$

where $f(E)$ is the function between D and E (see equation (4)); 0.287 and 0.031 are the maximum and minimum value of expectation of soil moisture, respectively.

Then $f^\bullet(E)$ is similar to $f(x)$, that is

$$\int_{0.031}^{0.287} f^\bullet(E)dE = 1 \qquad (7)$$

So it is got that:

$$P\{0.05 < E < 0.245\} = \int_{0.05}^{0.26} f^\bullet(E)dE = 0.8 \quad (8)$$

where P is probability.

Using probability theory (Sheng, et al., 2001), we consider that the interval (5%, 24.5%) of E is one of the suitable intervals, in which *P. euphratica* Oliv. grows well.

4 CONCLUSIONS

(1) Soil moisture in root zone changes any time, while growth of root system is slow, thus it is jadish to study the relationship between soil moisture and coarse root system of one tree. That is to say, the study should include the whole *P. euphratica* Oliv. trees. So choice of sample trees is the key factor to success of the experiment. Firstly, 200 *P. euphratica* Oliv. trees in the Protected Area are sampled at random, and mean value (μ) and standard error (σ) of DBH of each sample tree is measured. By analysis above, we know that the distribution of DBH obey normal distribution, among them we select independently and randomly 20 *P. euphratica* Oliv. trees which DBH are belong to the interval (μ -3 σ, μ +3 σ). Then sample trees are representative (Sheng, et al., 2001).

(2) Generally *P. euphratica* Oliv. trees grow better from May to July in a year. Moreover, the period is a water supply intermittent period by Heihe River upriver, so the change of soil moisture is small. Then the experiment is reasonable from May to July.

(3) For a fractal system, the exterior form is complex, while the fractal dimension is a constant. Roots distribution of tree has a typical fractal characteristic, thus, the root fractal

dimension should depict the characteristic of roots distribution. The more developed root distribution is, the bigger fractal dimension is. In the paper, we compute fractal dimension (*D*) of coarse root system of 20 *P. euphratica* Oliv. trees.

(4) Using fractal theory and statistical method, the function between fractal dimension (*D*) of coarse root system of *P. euphratica* Oliv. and mean soil moisture (*E*) in root zone is set up. That is, with mathematical method we depict the response of coarse root distribution of *Populus euphratica* Oliv. to soil moisture in root zone. To study root system by root excavation surely does a lot of damage to root systems, especially to plant in arid region. Now, by the function, only know soil moisture in root zone, can we deduce the distribution of coarse root system of *P. euphratica* Oliv.. And we get one of the suitable interval of mean soil moisture, that is (5%, 24.5%), in which *P. euphratica* Oliv. grows well. So we should judge the health state of root system by this interval.

(5) The methods and conclusions in the paper are helpful both to preserve *P. euphratica* Oliv. foresty, as well as the other plant and to use water resource effectively in the extreme arid region.

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中国極乾燥地帯における土壌水分に対する Populus euphratica Oliv.の根の分布応答

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概要

一般的に樹木の根は主根，側根システムと根毛システムに分かれる。根毛システムと同様，主根，側根システムは樹木の生長にとって重要である。2006 年 5 月から 6 月にかけて，中国内モンゴル自治区 Ejina Banner で観測したデータをもとに，フラクタル理論と統計手法を用いて Populus euphratica Oliv.の主根，側根分布と根の領域の土壌水分の関係を解析した。樹木の根は，フラクタル特性を有する。根の形状は複雑であるが，フラクタルであるためフラクタル次元（D）は一定である。そこで標本抽出したそれぞれの樹木の主根，側根システムの D と平均土壌水分（E）を求め，D と E の関係を得た。その結果，Populus euphratica Oliv.の主根，側根分布が，その領域の土壌水分の違いによりどのように変化するかを関数で示すことができた。この関数により，Populus euphratica Oliv.の主根，側根の分布を判定することができる。もし E が 11.02%以下であれば，フラクタル次元は E とともに増加し，11.02%以上であれば，E とともに減少する。この関数をもとに，Populus euphratica Oliv.がより成長する土壌水分量区間（5%，24.5%）を見いだした。

Keywords: extreme arid region, Populus euphratica Oliv., root distribution, soil moisture, root fractal dimension

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