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RESEARCH ARTICLE

Yankui WEI, Liming JIA, Ling WANG, Guoqing QIU, Changshan XING

Characteristics of root growth in a fast-growing and high-yield poplar plantation under subsurface drip-irrigation

Abstract The characteristics of root growth in the fast-growing and high-yield plantation of poplar I-214 (*Populus* × *euramericana* cv. 'I-214') were studied under two contrasting conditions, subsurface drip-irrigation (SDI) and normal irrigation (CK), on the sandy soil of Chaobai River, Beijing. The results showed that in the soil layer of 20–50 cm, there was a considerable increase in the amount of roots less than 10 mm in diameter (especially those of less than 2mm) under SDI, which was three times as much as that under CK. The absorbing roots under SDI were concentrated in the soil layer of 20–50 cm, while the roots under CK were distributed evenly in each layer. With respect to horizontal distribution, roots ($d < 10$ mm) under SDI were distributed mainly near the subsurface emitters and the amount of roots in 3 m in a row under SDI were 50% less than under CK. Therefore, it is suggested that subsurface emitters with the shape of "#" should be collocated in the middle of two rows and two individual trees to increase the distributing and absorbing range of roots under SDI, and further increase the plantation productivity.

Keywords poplar, fast-growing and high-yield plantation, subsurface drip-irrigation, roots

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Yankui WEI (✉)
Beijing Forestry Surveying and Planning Institute, Beijing 100029, China
E-mail: menglin77@163.com

Liming JIA, Ling WANG
The Key Laboratory for Silviculture and Conservation of Ministry of Education, Beijing Forestry University, Beijing 100083, China

Guoqing QIU
Shunyi District's Forest Bureau of Beijing, Beijing 101300, China

Changshan XING
Gongqing Forest Centre of Beijing, Beijing 101300, China

1 Introduction

The roots are the primary organ for plants to absorb water and nutrients from soil. They are the places where the organic compounds, such as aminophenol and amide, are synthesized, and also have great effects on chlorophyll formation and plant photoperiod reaction. It is theoretically and practically important to study the relationship between root growth and distribution and tree growth, as well as the factors affecting the configuration and distribution of tree roots, such as soil, stand age, and mixture models. Many forestry researchers pay interest to studies on roots (Whittaker, 1979; Zhai, 1982; Lakany, 1993; Dickmann, 1996; Xue, 2002; Lu, 2006). In the studies on poplar roots in sandy soil around the Chaobai River of Beijing, Xiang and Chen (1982) investigated the root characteristics of *Populus* × *canadensis*, including root form, hair roots in the soil profile and growth status of roots. Also, Chen (1982) studied the effects of different water tables, soils types (clay soil and sandy soil), soil porosities and mixture models on root systems.

The sandy soil along two major rivers, Chaobai River and Yongding River, is rather poor for afforestation. The low content of organic substances and the weak ability of water source conservation make the large area of fast-growing poplar plantation grow slowly, and thus result in low timber productivity. In view of the characteristics of sandy soil along the rivers, it is urgent to strengthen the management of water and fertility in woodlands to improve wood productivity. Therefore, based on a summary of irrigated forestation experience, we introduced an advanced water-saving irrigation technique, subsurface drip-irrigation (SDI), to improve poplar plantation in sandy soils. The SDI technique was applied in an area of 6.67 hm^2 of an experimental poplar I-214 plantation (*Populus* × *euramericana* cv. 'I-214') forested in the spring of 1997. The application has achieved some encouraging results so far. Compared with normal irrigation (CK), SDI increased the growth of poplar trees and the plantations' productivity. In

2000, the average diameter at breast height (DBH), height and volume per tree were 21.25 cm, 14.40 m and 0.1838 m^3 in SDI lands, which were 54.5%, 36.9% and 247.6% higher than under CK. The plantations' productivity under SDI reached 22.78 $m^3/(hm^2 \cdot year)$, 4.92 times as much as under CK, 4.63 $m^3/(hm^2 \cdot year)$ (Wei, 2003; Jia et al., 2004). In the present study, we investigated the characteristics of root growth under SDI and CK conditions to reveal further mechanisms with regard to fast growth and high yield of trees under the SDI technique, provide theoretical background and improve plantation productivity.

2 Experimental site

The experiment was carried out at the Haojiatuan department of the Gongqing Forest Centre of Beijing. The department lies along the Chaobai riverside, and the geographic coordinates are 40°16′N and 116°46′E, with an elevation of 30 m. The Gongqing Forest Centre was built in 1962 and the total area is 980 hm^2. The soil in the experimental site is alluvial sand with clay soil interlayer, whose bulk density is 1.5 g/cm^3, field capacity 13.8%–15.5%, saturated water content 40%–45%, and ground-water lever about 5 m. The content of organic substances is less than 0.5% and the ability of water and fertilizer conservation is poor. The area has a monsoon climate in the warm-temperate zone, with dry and windy spring and hot and rainy summer. The mean annual air temperature is 11.4°C and the mean annual accumulative air temperature is 5400°C. The mean annual rainfall is 630 mm, concentrating in July and August. The average annual evaporation is 2000 mm. The frost-free period is 180–200 days.

3 Materials and methods

3.1 Experimental design

The experimental site is located to the south of the Haojiatuan department and to its west is the Chaobai River. The area of the experimental site is 6.67 hm^2. I-214 poplars were planted in the spring of 1997 with a row spacing of 5 m × 6 m, 333 trees per hm^2. The seedlings were 2 years old with an average height of 4.5 m. All seedlings were transplanted with roots and repaired crown. The investigation started in May of 2002, when the average DBH and height were 22.4 cm and 14.5 m under SDI and 16.3 cm and 11 m under CK.

The experimentation included two treatments, i.e., subsurface drip-irrigation (SDI) and control (CK). The equipment of SDI is composed of a controller, stress jar, main pipelines, branch pipelines, control valves, capillary pipelines, subsurface emitters and so on. The controller was made by the USA RainBird Company and it can operate automatically or artificially. All of the subsurface emitters were laid 20 cm underground and they were disposed around each tree with a diameter of 70 cm. Socket irrigation was applied in CK.

Different irrigation regimes were applied in the SDI and CK since the afforestation in 1997. SDI site: The irrigation was 4–5 times in spring, 1–2 times in summer and once in autumn before the earth was frozen. The first irrigation in spring is in the last ten days of March. Irrigation continued 12 h each time but 24 h in autumn, and the irrigation discharge was 240 L per tree each time but 240 L per tree in the autumn. CK site: The socket irrigation was 1–2 times in spring, once in summer and once in autumn before the earth was frozen. The irrigation discharge was 640 L per tree each time.

Carbamide was applied in 1997 and ammonium nitrate starting 1998. Fertilization was carried out with irrigation for 6 times and 0.15 kg per tree each time in SDI. Furrow fertilizing was carried out twice, 1 kg in total in CK.

3.2 Methods

3.2.1 Investigation of roots ($d < 10$ mm) in the experimental sites

The investigation of roots ($d < 10$ mm) started from two aspects. One was distribution of roots ($d < 10$ mm) in the whole woodland. Another was distribution of roots ($d < 10$ mm) in different distances apart from the standard tree.

1) Distribution of roots ($d < 10$ mm) in the whole woodland

Root amount was investigated using the soil column method (Zhai, 1982). According to the characteristics of the uniform distribution of plantation trees, the distribution of roots ($d < 10$ mm) in the experimental sites (SDI site and CK site) was investigated by the method of soil column. The soil columns were set in the nearest and farthest distance away from trees in the rows and in the diagonal of trees in order to diminish the impact of different distances from trees in the woodland. Because a round pipe with a diameter of 70 cm and with 10 evenly-distributed emitters on it was buried around each tree, the nearest soil column was 1.2 m away from the tree in order not to destroy the subsurface emitters. The location of the farthest soil column was determined to be the midpoint of the nearest two trees in each direction, i.e., 3.0 m in the row direction, 2.5 m in the space direction and 3.9 m in the diagonal direction (Fig. 1). At the points of 1.2 and 3.0 m in row, 1.2 and 2.5 m in space and 1.2 and 3.9 m in diagonal, the sampling of the soil column was repeated three times. In total, 18 columns were sampled and evenly distributed in the experimental sites.

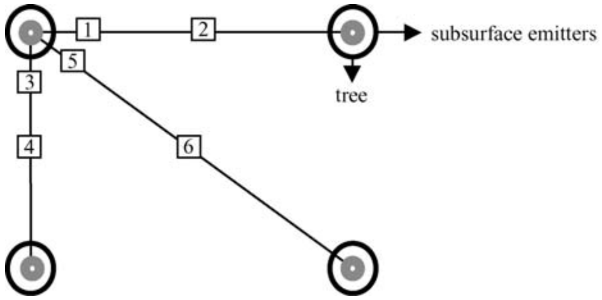

Fig. 1 Distribution of investigation site of roots ($d <$ 10 mm) in the woodland
1. At the location of 1.2 m in the rows; 2. At the location of 3.0 m in the rows; 3. At the location of 1.2 m between trees; 4. At the location of 2.5 m between trees; 5. At the location of 1.2 m in the diagonal of trees; 6. At the location of 3.9 m in the diagonal of trees.

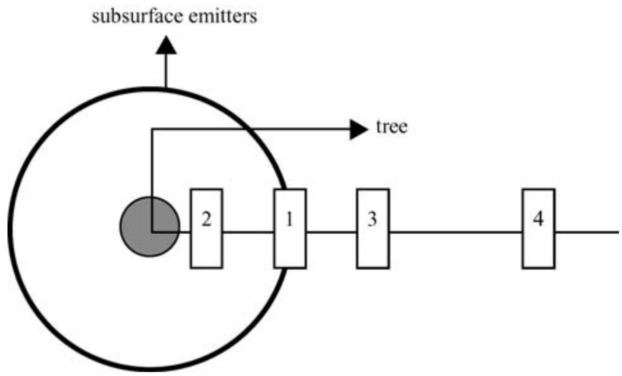

Fig. 2 Distribution of investigation site of roots ($d <$ 10 mm) in different distance from standard tree
1. At the place of subsurface emitters; 2. 40 cm inside to subsurface emitters; 3. 40 cm outside to subsurface emitters; 4. 110 cm outside to subsurface emitters.

Each column was 50 cm × 50 cm in area and divided into layers of 0–20 cm, 20–50 cm, 50–80 cm and > 80 cm. All roots in each layer were collected and cleaned. The roots were graded into three diameter classes: less than 2 mm (fine roots), 2–10 mm (thick roots) and more than 10 mm (skeleton roots). The roots were oven dried at 80°C for more than 8 h and weighed immediately after their weight stayed constant. The root amount of the whole woodland was calculated based on the roots in the soil columns. Then, the average root amount of individual trees was converted according to the tree density in the woodland.

2) Distribution of roots ($d <$ 10 mm) at different distances to the standard tree

Roots ($d <$ 10 mm) at different distances to the standard tree were investigated based on the biomass of average standard trees. The soil was dug out carefully in layers from the distance of about 2 m to the standard tree from three directions, i.e., the south, the west and the north. The method of soil column was also applied. Soil columns were set in places of 40 cm inside the subsurface emitters, 40 cm outside the subsurface emitters and 110 cm outside the subsurface emitters (Fig. 2). The soil column size was 20 cm × 50 cm (in the tangent direction along the subsurface emitters) and divided into layers of 0–20 cm, 20–50 cm, 50–80 cm and > 80 cm. Others were the same with that of the method of the soil column.

3.2.2 Investigation of root form

Root form was investigated by exposing roots of an average standard tree. After investigating the distribution of roots ($d <$ 10 mm) at different distances from the standard tree, the roots were dug out in layers from the distance of about 2 m to the standard tree. The form and distribution of roots were observed; their vertical section was protracted and photographed according to the root length, thickness and extension direction.

4 Results and discussion

4.1 Comparison of root form in SDI and CK

The form of skeleton roots observed by the method of exposure is shown in Figs. 3 and 4.

Fig. 3 The form of skeleton roots of poplar in the SDI site

Fig. 4 The form of skeleton roots of poplar in the CK site

The taproot of the poplar tree is 52.5 cm long and the total wet roots weighed 46.6 kg in the SDI site, while it was 39 cm long and 24.6 kg in the CK site. The tree age both in SDI and in CK was 7 years. There were seven side roots with a basal diameter larger than 8 cm on the taproot in SDI but two in CK. There were 17 side roots with a basal diameter of 1–8 cm in SDI but 23 in CK. There were four skeleton roots on the groundwork and all of their basal diameters were more than 8 cm in SDI, but three in CK and only one of them had a basal diameter larger than 8 cm. A large number of fine roots attached closely on the skeleton roots in SDI but few in CK. The basal diameters of most roots in CK were 1–6 cm and distributed evenly. It is suggested that SDI can strengthen the root system of trees generally in the woodland, increase the length of taproots which play a propping function, enhance the number of bigger side roots and absorbing roots, and increase the root amount. Especially, the rise in the number of fine roots is beneficial to the uptake of water and nutrients of trees.

4.2 Distribution of roots ($d < 10$ mm) in the woodland

4.2.1 Amount of total roots ($d < 10$ mm) in the woodland

The study showed that the amount of total roots ($d < 10$ mm) in the woodland was 1896.8 kg/hm^2 in SDI but 1413.6 kg/hm^2 in CK, in which the amount of total fine roots ($d < 10$ mm) was 657.6 kg/hm^2 and that of total thick roots (2–10 mm) was 1239.2 kg/hm^2 in SDI but 349.2 and 1064.4 kg/hm^2 in CK. Compared with CK, SDI had a big improvement in the amount of total roots, total fine roots and total thick roots, 34.18%, 88.32% and 16.42%, respectively. It is suggested that SDI can increase the amount of roots ($d < 10$ mm), especially that of fine roots ($d < 2$ mm) whose water absorbing ability is very strong. This is the important reason for the increase of the tree's growth and productivity of the plantation.

4.2.2 Vertical distribution of roots ($d < 10$ mm)

In Fig. 5, both fine roots and thick roots in SDI were concentrated in the soil layer of 20–50 cm, accounting for 49% and 48% of the total roots. There were few roots in the soil layer of > 80 cm and there was little difference between the other two layers. Because subsurface emitters were set 20 cm underground, it is obvious that roots ($d < 10$ mm) were concentrated in the soil layer which was affected most by water infiltrating from the subsurface emitters. In Fig. 6, there is no root in the soil layer of > 80 cm and the difference in the amount of fine roots in the other three layers is not notable, but with more thick roots in the soil layer of 20–50 cm. It shows that, since water in CK is not supplied as constant as in SDI, roots distribute more evenly to absorb as much water as possible from the soil to satisfy the need for the tree's growth.

There were more roots in the soil layer of 20–50 cm both in SDI and CK, but the amount of fine roots in SDI

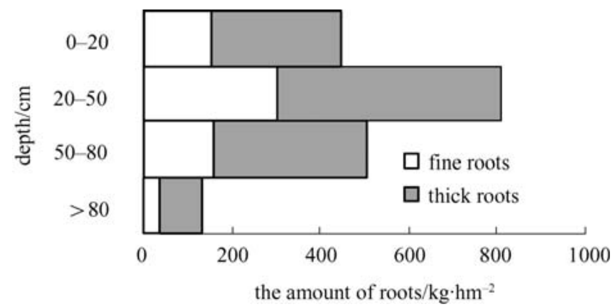

Fig. 5 Distribution of poplar roots ($d < 10$ mm) in SDI site

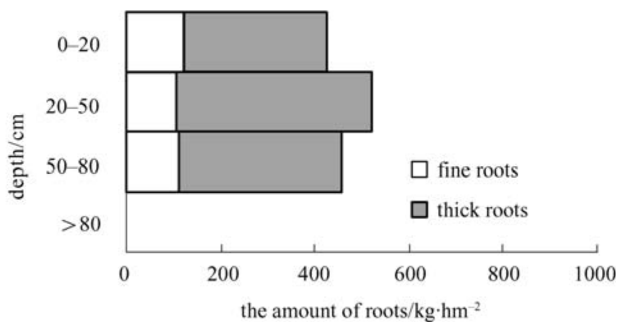

Fig. 6 Distribution of poplar roots ($d < 10$ mm) in CK site

is 2.9 times that in CK and the amount of thick roots in SDI is 20.8% more than that in CK. Because subsurface emitters were set 20 cm underground, water and nutrients in the soil layer of 20–50 cm were affected most by irrigation. Thus, the marked increase of the amount of absorbing roots, especially that of roots $d < 2$ mm, reflects the roots' characteristics of inclination to water and nutrients, and greatly enhances the trees' ability of absorbing water and nutrients in SDI. This is the important reason for the increase of the trees' growth and plantation productivity in SDI.

4.2.3 Horizontal distribution of roots ($d < 10$ mm)

1) Horizontal distribution of roots ($d < 10$ mm) in SDI

In the woodland, the distribution of roots at different distances and in different directions from trees is shown in Figs. 7–12. It is shown that the vertical distribution of roots both between trees (Figs. 7 and 10) and between rows (Figs. 8 and 11) presents the tendency of "more in the middle layers and less in the upper or lower layers". Most of the roots concentrated in the soil layer of 20–50 cm and fewer in the soil layers of 0–20 cm, 50–80 cm and > 80 cm. In the diagonal of trees (Figs. 9 and 12), the roots in the soil layer of 50–80 cm amounted most at the location of 1.2 m and that in the soil layer of 0–20 cm accounted for the most at the location of 3.9 m, which shows that subsurface emitters have little effect on this location, and the distribution of roots in these soil layers are more influenced by rainfall than by emitters. In any soil layer, there are more roots at the locations nearer the trees and fewer further from the trees. The location of 1.2 m in the rows had the most amount of both fine roots and thick roots, either at different distances or in different directions, which reach 29.8 and 56.23 g per soil column. However, the root amount at the location of 3.9 m in the diagonal of trees is the least—only 12.9 and 15.85 g per soil column. In the farthest distance in different directions, namely, at the location of 2.5 m between trees, 3.0 m in the rows and 3.9 m in the diagonal of trees, the soil layers of 0–20 cm and 20–50 cm are the main distribution areas of roots, much more at the location of 2.5 m between trees than 3.0 m in the rows and 3.9 m in the diagonal of trees. Because the trees are planted in a spacing of 5 m × 6 m, it seems that irrigation of subsurface emitters from both sides can still benefit the location of 2.5 m between trees, but there is little effect on the location of 3.0 m in the rows and 3.9 m in the diagonal of trees as they are farther away from the emitters. Therefore, it is suggested that with the growth of trees and the extension of roots, more #-shaped subsurface emitters should be set in the middle of two rows and two individual trees to increase the distribution range of roots under SDI for the purpose of fast growth and high yield.

2) Horizontal distribution of roots ($d < 10$ mm) in CK

There were almost no roots in the soil layers of > 80 cm in CK (Figs. 13–18). The roots between trees distributed mostly in the soil layer of 20–50 cm (Figs. 13 and 16) and that in the rows were concentrated in the soil layer of

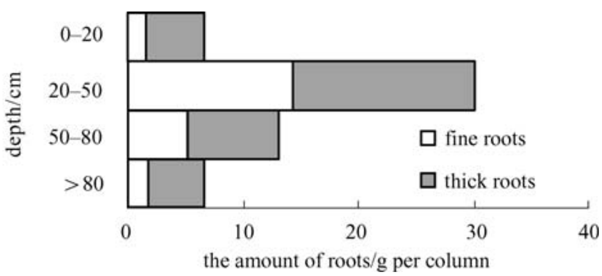

Fig. 7 Distribution of poplar roots at the location of 1.2 m between trees in SDI

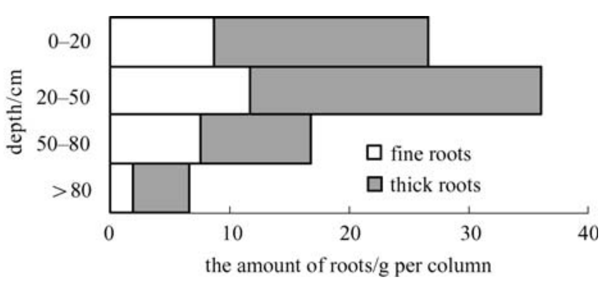

Fig. 8 Distribution of poplar roots at the location of 1.2 m in the rows in SDI

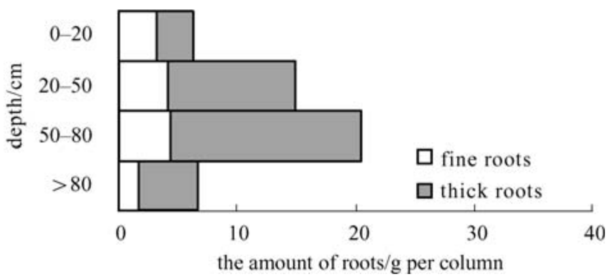

Fig. 9 Distribution of poplar roots at the location of 1.2 m in the diagonal of trees in SDI

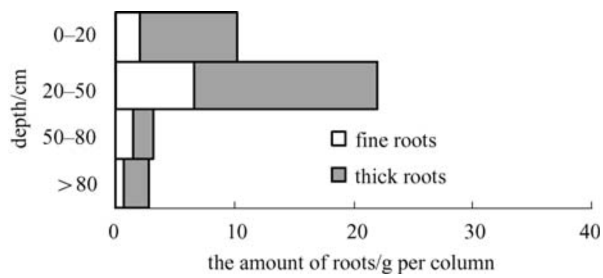

Fig. 10 Distribution of poplar roots at the location of 2.5 m between trees in SDI

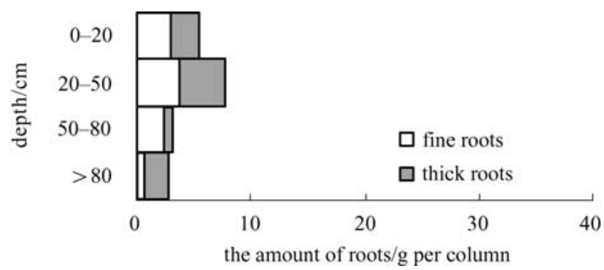

Fig. 11 Distribution of poplar roots at the location of 3.0 m in the rows in SDI

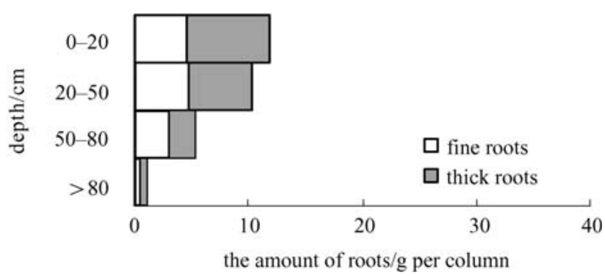

Fig. 12 Distribution of poplar roots at the location of 3.9 m in the diagonal of trees in SDI

50–80 cm, while the roots in the diagonal of trees were distributed evenly in every layer but a little more in the soil layer of 0–20 cm (Figs. 15 and 18). Different from that in SDI, the amount of both fine roots and thick roots were the most in the diagonal of trees, 1.57 times and 1.25 times, respectively, as much as that between trees. Trees in CK were irrigated only by rainfall 3–4 times per year and the soil moisture was low. The competition for water among trees was very severe.

Comparatively, there is a rather big space for roots to absorb water and nutrients in the diagonal direction. At the farther distance in the diagonal of trees, roots competed weakly and distributed mostly in the upper soil layers where rainfall and irrigation could reach easily, while at the nearer distance, roots had a more severe competition and absorbed water and nutrients only from deeper layers to satisfy the need of tree growth.

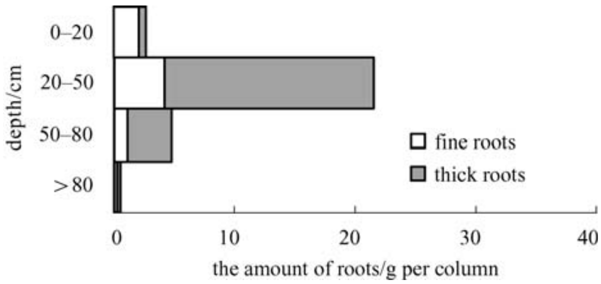

Fig. 13 Distribution of poplar roots at the location of 1.2 m between trees in CK

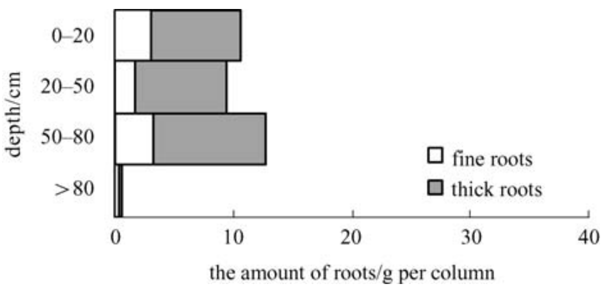

Fig. 14 Distribution of poplar roots at the location of 1.2 m in the rows in CK

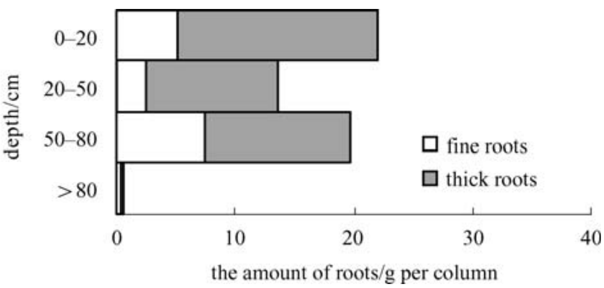

Fig. 15 Distribution of poplar roots at the location of 1.2 m in the diagonal of trees in CK

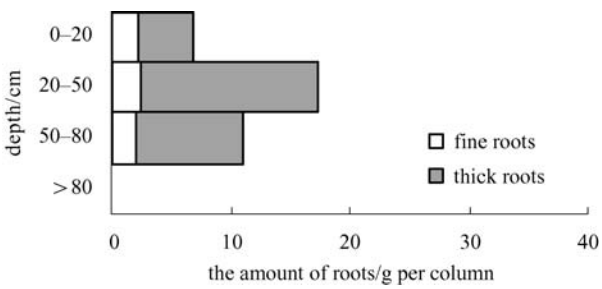

Fig. 16 Distribution of poplar roots at the location of 2.5 m between trees in CK

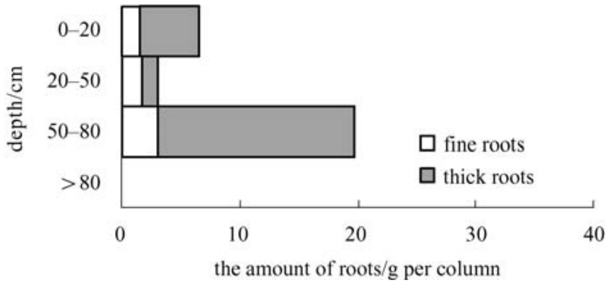

Fig. 17 Distribution of poplar roots at the location of 3.0 m in the rows in CK

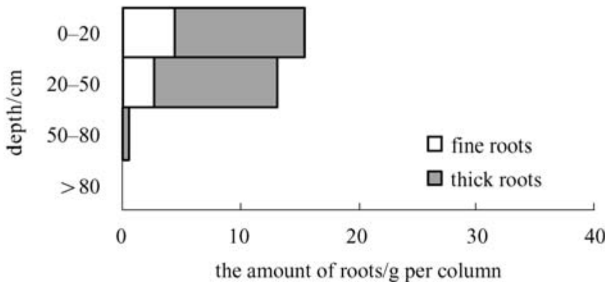

Fig. 18 Distribution of poplar roots at the location of 3.9 m in the diagonal of trees in CK

Distribution of roots in CK woodland represents the natural state of tree growth and that in SDI shows a distribution in the special condition of SDI, and the amount of roots increase in the areas around the subsurface emitters where seeped water can reach. The amount of all roots at the location of 2.5 m between trees, 3.0 m in the rows and 3.9 m in the diagonal of trees in CK is more than or as much as that in SDI, which shows that the roots cannot distribute to this distance but are caused by the effect of distribution of subsurface emitters. So it is suggested that #-shaped subsurface emitters should be set in the middle of two rows and two individual trees to increase the absorption range of roots under SDI, and further increase the productivity of the plantation.

4.3 Horizontal distribution of roots ($d < 10$ mm) at different distances from individual trees

Horizontal distribution of roots ($d < 10$ mm) at different distances from individual trees in SDI and CK are shown in Figs. 19 and 20. Though at different distances from the tree, the amount of both thick roots and fine roots at each distance in SDI was evidently more than that in CK, but there was no notable difference at the distance of 170–190 cm from trees between SDI and CK. We consider that it was possibly caused by the reason that water seeped from subsurface emitters had no marked effect on the soil moisture at this distance, which makes the soil moisture content far from the trees between SDI and CK not markedly different. As for the amount of fine roots, there was no big difference at the first three distances, while there was no evident difference for the amount of thick roots at the first two distances but they were quite different to that at the third distance, such as the amount of thick roots at the 60–80 cm distance to the trees was 1.5 times as much as that at the 100–120 cm distance. At the horizontal distances from near to far, the amount of fine roots in SDI were 27.8%, 74.88%, 68.9% and 0.4% more than that in CK. The amount of thick roots of the first two are 2.6% and 50.43% more than and that of the last two, which were 13.4% and 18.2% less than that in CK. The amounts of thick roots at 100–120 cm and 170–190 cm distances in the horizontal direction in CK were more than that in SDI instead, which showed that fine roots made up for most of the increased amount of roots in SDI. Especially, the increase reached 74.88% at the 60–80 cm distance in the horizontal direction.

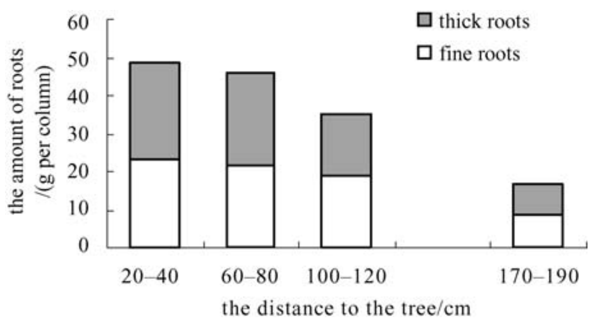

Fig. 19 Horizontal distribution of poplar roots of individual plants in SDI site

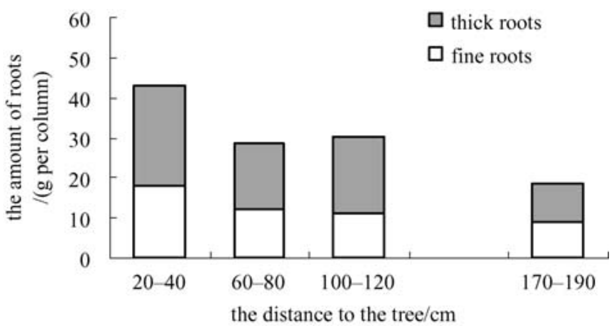

Fig. 20 Horizontal distribution of poplar roots of individual plants in CK site

In SDI, the amount of all roots at the place of subsurface emitters (70 cm from the center of the tree) was 1.75 times as much as that in CK, and there was little difference between the place of subsurface emitters and the place inside subsurface emitters, but both had marked difference from the place outside of subsurface emitters. In CK, the amount of all roots at 20–40 cm distance from the tree was not evidently different from that at other distances in the horizontal direction. SDI can increase not only the roots at the place of subsurface emitters but also at other distances.

5 Conclusions and suggestions

The root form in SDI and CK showed that SDI not only could increase the biomass and the amount of skeleton roots but could also increase the amount of absorbing roots. The result of further studies showed that the amount of roots ($d < 10$ mm) in SDI is 34.2% more than that in CK, in which that of roots ($d < 2$ mm)) in SDI is 88.3% more than that in CK. The big increase of the amount of absorbing roots played a key role in increasing the uptake of water and nutrients in SDI. This is one of the important reasons of increasing the productivity of the plantation. As absorbing roots ($d < 10$ mm) distributed vertically in the woodland, the roots in SDI concentrated in the soil layer of 20–50 cm, while the roots in CK distributed evenly in every layer but a little more in the soil layer of 20–50 cm. As for the horizontal distribution of absorbing roots ($d < 10$ mm) in the woodland, roots under SDI had a considerable decrease with the increase of distance to trees. The roots in CK also followed this rule but the decreasing trend is small. These show that the roots cannot distribute to a distance far from the trees but are affected by the distribution of subsurface emitters. Therefore, it is suggested that the #-shaped subsurface emitters should be set in the middle of two rows and two individual trees to increase the absorption range of roots in SDI, and further increase the productivity of plantations.

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