Environmental Engineering and Management Journal

December 2020, Vol.19, No. 12, 2113-2119
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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ROOT SYSTEM CHARACTERISTICS OF THREE WOODY SPECIES PLANTED ON STEEP SOIL-DENUDED SLOPES

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Abstract

This paper aims to investigate the root characteristics of three woody species *(Pinus brutia, Quercus coccifera* and *Spartium junceum*) planted on steep soil-denuded slopes, surfaced after ring-road excavation. The planted slopes were almost vertical, south faced and adding no soil. Fifteen plants per species were manually extracted for root system analysis and testing. The findings showed that the survivorship was different among the investigated species with *S. junceum* plants to survive better. The studied species follow different patterns of root development which in all cases were strongly affected by the adverse site conditions. The taproots, in all cases, got tapered and shortened rapidly in the length of the digging hole's depth, while the density of lateral roots increased, especially in the case of *S. junceum*. Root tensile breaking force differed among the species and it was found to correlate with root diameter. The resistance force from the cracks resulted in a deformation of embedded roots (flat-shaped roots instead of circular). The specific adaptation, which enables the plants to persist in such adverse environments, seems to be the number of embedded roots which were constant among the three studied species. However, based on the overall species performance, *S. junceum* appeared to be the best adaptable for eco-engineering purposes.

Key words: highways restoration, root deformation, root tensile resistance

Received: April, 2020; Revised final: October, 2020; Accepted: November, 2020; Published in final edited form: December, 2020

1. Introduction

The restoration of human-disturbed habitats after civil constructions is a difficult task requiring great effort by environmentalists in order to link and connect the disturbed area to the surrounding natural habitats. Landscape connectivity is a key aspect for the maintenance of biodiversity and ecosystem viability. Thus, the long term establishment of woody vegetation on the disturbed lands is a common strategy for the mitigation of the construction effects and land safety. However, the vegetation establishment in excavated lands with steep slopes, with shrubs and trees is usually quite difficult due to extreme microclimatic and edaphic conditions (Beikircher et al., 2010; McGrath et al., 2020). During many restoration projects, there are a lot of cases where the root systems of the planted species are challenged to grow on limited soil or soil-denuded slopes, mainly by developing a strategy for finding water and nutrients in cracks within the bedrock (Li et al., 2007). In these cases, there is no available soil for root system development apart from the limited available space within the digging planting hole.

The knowledge of the rooting events taking place in plants growing on slope is necessary for eco-engineering purposes (Stokes et al., 2008a). However, not much is known about root system characteristics of plants grown on shallow soils over bedrock or massive hardpans (Schenk, 2008), and much less investigated have been the effects of rocky slopes (Li et al., 2007), or artificial steep soil-denuded slopes on root system of woody species. The depth of soil of rocky eco-engineering slopes is rather shallow (usually less than 15 cm), and thus the underlying bedrock limits the vertical growth of roots since the

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roots are unable to penetrate it (Nicoll and Ray, 1996; Stokes et al., 2008b). Surprisingly, a disproportionate number of rare species occurs in shallow, rocky and drought-prone environments (Poot and Lambers, 2008).

Roots of woody plants on shallow soils tend to grow along fractures deep into underlying rocks (Sternberg et al., 1996). In the cases of shallow soils and limited plant-available water it is assumed that roots may address to cracks within the decomposed bedrock that provide access to water and nutrients (Poot and Lambers, 2008; Sternberg et al., 1996).

Although, the importance of root system architecture for the stability of trees grown on slopes has received considerable attention (Fan and Chen, 2010; Tsige et al. 2020), there are very limited studies on the root system development pattern on artificial steep slopes surfaced after road construction. Among the most widespread forms of landscape modification is the road construction and its effects are of great concern to landscape and ecosystem managers as well as to the communities (Karim and Mallik, 2008; Jia et al., 2020). For an effective ecological restoration of the disturbed peri-road environments, sound ecological knowledge on the newly roadside habitat and attributes of the colonizing species and mechanisms developed by them, is required.

The selection of the suitable native plant species that can survive and grow under the above mentioned adverse conditions is a critical issue for vegetation establishment (Bochet et al., 2010; Ganatsas and Tsakaldimi, 2003). Plant root characteristics adapted to these specific site conditions may prove essentials for indication of plant adaptation mechanisms.

In this study, root system characteristics (architecture, deformation, tensile force at failure) of three woody plant species *(Pinus brutia,* a Mediterranean pine*, Quercus coccifera,* an evergreen oak, and *Spartium junceum*, a nitrogen fixing species of the Fabaceae family), were measured five years after their artificial establishment on artificial steep slopes, surfaced after ring-road construction and the entire removal of soil material. In particular, the study was focused on the investigation of any differences on species growth, root development and adaptation under these specific site conditions, focusing on species adaptation for finding crevices in underlying bedrock, thereby increasing their chance of obtaining water and nutrients.

The selected species belong to different functional groups and present root systems with considerable morphological differences and therefore it is reasonable to hypothesize that they differ considerably in the mechanism developed by their roots in order to achieve good anchorage and survival under these adverse site conditions. Moreover, these woody species have been widely used on artificial slopes for slope eco-engineering because of their high drought tolerance, which is a prerequisite for the restoration of these sites (Beikircher et al., 2010).

2. Materials and methods

2.1. Site details

The study was conducted in the peri-urban area of Thessaloniki, northern Greece. The altitude ranges from 150-200 m. Geologically, the area belongs to the magmatic series of Chortiatis and consists mainly of green-schist. According to the nearest meteorological station of University of Thessaloniki, the climate is Mediterranean with a mean annual precipitation of 420 mm, while the dry season lasts from April or middle of May to the end of September. Floristically, the area belongs to the Ostryo-carpinion alliance (Tsitsoni et al., 2004). The soils are slightly acid and they are characterized by weak structure, low porosity, and high percentage of stones lamarand pebbles (Ganatsas and Spanos, 2005). The area is characterized by adverse ecological conditions, namely, shallow soil, high mechanical resistance of the underground bedrock and low water availability during the long dry summer (Ganatsas and Tsakaldimi, 2003; Ganatsas and Spanos, 2005), this latter resulting to the main limiting factor for plant survival and growth (Ganatsas and Tsakaldimi, 2003).

The studied areas were artificially steep soil-denuded highway-cut slopes, surfaced by the construction of the ring road. The bedrock consists of schist with cracks formed in several directions. The slope-sides are almost vertical, and their depth, from the land surface, ranges from 2 to 5 m. No soil or other material was added on the slopes surface. For the restoration of the roadside slopes, planting with woody species had been carried out in 2002. The seedlings were manually planted in digging holes (18 cm width x 20 cm depth) which had been mechanically excavated. According to the Restoration Plan of the highway the three selected woody species *P. brutia, Q. coccifera* and *S. junceum* had been planted as two-years old containerized seedlings (grown on plastic bags 12 x 16 cm), and their initial average height was 31.4 cm, 26.8 cm, and 34.5 cm respectively. No root measurements were made at the time of planting. The species survival was recorded five years after planting.

2.2. In situ excavations

Five years after planting, in October 2007, 15 plants per species were manually extracted for root system analysis. Sampling was randomly carried out in the south-faced slope-sides of the ring-road. To reduce mechanical damage, the root systems were excavated by hand (Fan and Chen, 2010; Spanos et al., 2008), using a small shovel and trowel and working progressively starting from the collar, carefully removing the soil and exposing the root system. All roots of each root system were cleaned from soil material by using a paint brush. Actually it was quite difficult and time-consuming to excavate root systems in rock cracks. It may take almost 5h to excavate the root system of a plant by battering the rock with a small pickaxe and a small hoe, and the digging depth sometimes may reach over 0.5-0.6 m. Unfortunately, there are no alternative methods to hand excavation for recovering entire root systems under such site conditions (Chiatante et al., 2003a; Chiatante et al., 2003b; Danjon et al., 2008). After the excavation, the root systems were prepared for measurements by removing any soil material around them.

2.3. Measurements

For each excavated plant, the following parameters were manually recorded in the field, using a tape for length measurements, and a vernier calliper for diameter measurements, with an accuracy of 0.1 cm and 0.1 mm, respectively: root collar diameter (mm), shoot height (cm), taproot length (cm), number of coarse roots (d > 5 mm), number of first, second and third order laterals of medium roots (1 mm < d < 5 mm); morphometric root ordering used for medium roots was according to Fisher and Jayachandran (1999) and Walter (1980), number of fine roots (d < 1mm) regardless the number of order, number of roots exceeded the space of digging hole, length and diameter of the three longer roots of each plant whenever they were developed, and number of roots penetrated into rock cracks. Any observed root deformation (whirling, tapered roots, flat-shaped roots into the rock cracks etc) was recorded as well. For any observed flat-shaped root the ratio of height/width, instead of diameter, was estimated. Each root system required about one day for excavation and measurements.

After excavation and *in situ* measurements, samples of root systems were transported to the laboratory for root tensile testing (Tsige et al., 2020). Laboratory root tensile tests were conducted on 12 cm long root samples (30 per species) in the Laboratory of Wood Technology of Aristotle University of Thessaloniki, using the apparatus SHIMAZDU UH-300kNA. Tests were performed about two hours after removing the root samples from the field, and keeping them in moist conditions to avoid moisture losses (Preti and Giadrossich, 2009). Root diameter at the midpoint was measured prior to test performance. To force the failure in the middle part of the root, both root ends were glued with an epoxy resin (Tosi, 2007) adhesive over 20 mm. The root samples were pulled up vertically at 8 mm/min in the testing equipment. During the test, measurement of force had been automatically obtained. We recorded and presented here the value of maximum tensile breaking force of the root samples. Statistical analysis was carried out by SPSS statistical program. One-way ANOVA was performed for the means comparison using the Waller-Duncan test (P < 0.05, Norusis, 2002).

3. Results

Five years after planting on the steep soil-denuded roadside slopes, the average survival of the tree studied species was 36.2% for *Q. coccifera,* 44.6% for *P. brutia* and 58.8% for *S. junceum* (data not shown). The above-ground growth of the three woody species was relatively low; *S. junceum* plants found taller compared to other species and exhibited a mean height 92.7 cm, while *Q. coccifera* plants were only 51.4 cm. The average height annual growth was 11.64 cm for *S. junceum,* 9.98 cm for *P. brutia* and 4.92 cm for *Q. coccifera*. No significant differences were detected in root collar diameter which ranged from 16.1 mm to 20.0 mm among the three species (Table 1).

All the root systems of the three woody species faced strong difficulties to penetrate the impermeable walls of the digging hole. The taproots of all studied plants got tapered and shortened rapidly as the length exceeded digging hole's depth, due to the impenetrable underlying bedrock. Thus, the average length of all taproots was 16.3 cm (Table 2), approximately the depth of digging hole, and only in some cases, the taproot continue to grow horizontally (or sideways) after the digging hole's depth, into less impenetrable bedrock material. Moreover, few (2-3) strong coarse lateral roots (d > 5 mm) developed radially from the taproot.

The number of medium and fine roots was much greater than that of coarse roots, and presented significant differences among the root systems of the studied species (Table 2). *S. junceum* plants produced the more fibrous root system; the number of fine roots of *S. junceum* was found approximately two and six times greater than that of *P. brutia* and *Q. coccifera* respectively. Concerning the three longest roots, they were found significantly longer and thicker in the case of *S. junceum* plants (100.6 cm and 9.5 mm respectively). Moreover, *S. junceum* had significantly higher number of third order medium roots, while *Q. coccifera* plants presented the fewer medium and fine roots in relation to the other two species (Fig. 1).

It must be noted that, among all the studied root systems, only 3-4 roots, on average, managed to grow outside the digging hole into deeper layers or most often sideways (Table 3).

Table 1. Plant above-ground morphological characteristics of the three woody species, five years after planting

Above-ground morphological characteristics	*P. brutia*	*Q. coccifera*	*S. junceum*
Shoot height (cm)	81.3 (1.6) b	51.4 (2.7) c	92.7 (1.2) a
Root collar diameter (mm)	19.8 (1.5) ns	16.1 (1.0) ns	20.0 (0.8) ns

Values are the mean of 15 replicates ± SE (in parenthesis). Values followed by different letter are significantly different (Waller-Duncan test, P<0.05). Means followed by ns are not significantly different (P>0.05).

Table 2. Root system parameters of the three woody species

Root system parameters	***P. brutia***	***Q. coccifera***	***S. junceum***
Taproot length (cm)	16.2 (0.2)ns	16.5 (0.3)ns	16.3 (0.3)ns
Number of coarse roots (d > 5mm)	2.7 (0.8) ns	2.1 (0.1) ns	3.1 (0.3) ns
Number of medium roots (1mm> d> 5mm)	40.3 (4.0) a	24.7 (1.8) b	36.4 (1.4) a
Number of fine roots (d<1mm)	106.5 (18.5) b	38.0 (4.6) c	242.2 (18.7) a
Length of longer root (cm)	98.2 (9.2) ab	80.0 (5.7) b	111.5 (6.2) a
Diameter of longer root (mm)	7.2 (1.1) b	11.0 (0.9) a	12.7 (0.4) a
Average length of the three longest roots (cm)	79.1 (4.08) b	69.2 (3.76) c	100.6 (4.72) a
Average diameter of the three longest roots (mm)	5.6 (0.310) c	8.0 (0.38) b	9.5 (0.64) a

Values are the mean of 15 replicates ± SE (in parenthesis). Values followed by different letter are significantly different (Waller-Duncan test, P<0.05). Means followed by ns are not significantly different (P>0.05).

Table 3. Root system deformation characteristics of the three studied plant species

Root deformation characteristics	***P. brutia***	***Q. coccifera***	***S. junceum***
Number of roots outside the root ball (or digging hole)	4.0 (0.6)	3.3 (0.7)	4.0 (0.1)
Number of roots exhibited whirling	Almost all the first-order laterals	3.4 (first-order laterals)	1.6 (first-order laterals)
Number of flat-shaped root embedded in cracks	2.0 (0.2)	3.2 (0.3)	2.7 (0.2)
Height/Width of flat-shaped roots	0.7 (0.05)	0.2 (0.03)	0.6 (0.07)

Values are means of 15 replicates ± S.E. (in parenthesis).

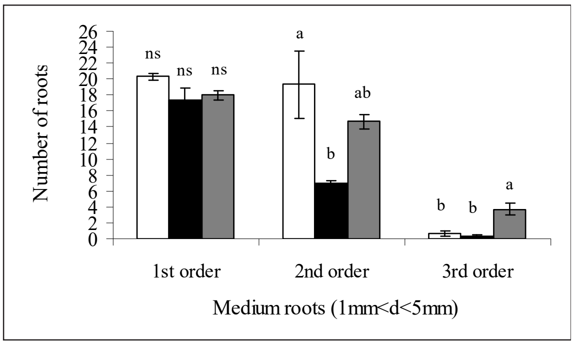

Fig. 1. Number of medium roots (1<d<5 mm) by root order (1st, 2nd and 3rd) for each studied species: *P. brutia* (white bars), *Q. coccifera* (black bars) and *S. junceum* (grey bars). Within each root order, bars are means of 15 replicates ± S.E.. For the same order laterals, bars without a common letter are significantly different (Waller-Duncan test, P<0.05)

However, the development pattern of the root systems was different in the three species. Almost all the first-order lateral roots of *P. brutia* grew cycled (exhibited whirling) mainly within the root ball or digging hole, while, in the case of *Q. coccifera* and *S. junceum* plants, only few first-order lateral (average 3.4 and 1.6 respectively) exhibited whirling. Most of the roots expanded outside the space of digging hole, especially the coarse and medium roots embedded in the bedrock cracks, whereas only a scarce number of fine roots were found within the cracks. In all cases, the roots outside the digging holes faced difficulties in their elongation process, and they usually zigzagged in order to elongate through the bedrock material.

The roots anchored in cracks exhibited a deformation (flat shape instead of circular), especially in the areas where the cracks width was smaller than the sizes of the roots on the bedrock surface (Table 3). Embedded roots of *Q. coccifera* exhibited a more extreme flat shape than embedded roots *P. brutia* and *S. junceum*. The ratio height/width of flat-shaped roots ranged from 0.2 for *Q. coccifera* to 0.6 and 0.7 for *S. junceum* and *P. brutia* respectively. In some cases the roots of *C. coccifera* plants were transformed to the form of a tissue-paper, with a ratio height/width lower than 0.1.

Laboratory analysis showed that root tensile breaking force greatly differed among the studied species (Fig. 2). *S. junceum* showed significantly greater values in all diameter classes, followed by *Q. coccifera*. In all species the root tensile breaking force significantly increased with root diameter.

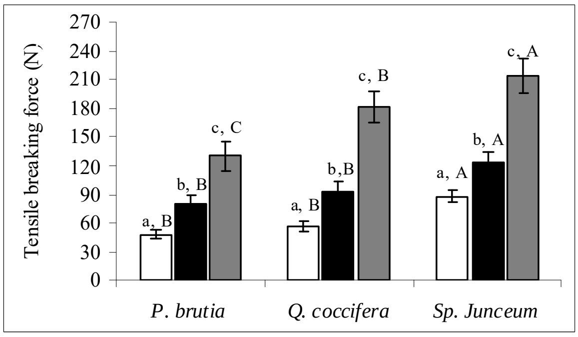

Fig. 2. Tensile breaking force of the root samples, in diameter class of the three studied species: 1.0-2.5 mm d at midpoint (white bars), 2.5-5.0 mm d at midpoint (black bars) and 5.0-9.5 mm d at midpoint (grey bars). Bars are means of 15 replicates ± S.E. Within the species, bars followed by different low case letter (a.b,c) are significantly different (Waller-Duncan test, P<0.05). Within the same diameter class, bars followed by capital letter (A,B,C) are significantly different (Waller-Duncan test, P<0.05)

4. Discussion

From the results obtained, it seems that the unfavourable habitat conditions (steep soil-denuded roadside slopes, shallow soil and high mechanical resistance of the underground bedrock) negatively affected the above-ground growth of the three studied species which was found relatively low. However, the survivorship was different among the investigated species and *S. junceum* plants showed significantly higher survival. This can be explained by the fact that during the hot and dry summers, when water is limited, *S. junceum* plants are leafless. These decreases in leaf area presumably leads to a decrease in the amount of water lost through transpiration.

Concerning the below-ground plant growth, the taproots in all studied plants got tapered and shortened rapidly in the length of digging hole's depth due to the impenetrable underlying bedrock. There were only few (2-3 on average) strong coarse lateral roots, which developed radially from the taproot. Except the restriction of taproot length, there was a relatively great development of lateral roots which followed different pattern among species. According to Coutts and Nicoll (1991), at an earlier stage of plant development, the taproot is the most vigorous root within the root system but its importance decreases as that of the lateral roots increase; this is common to both broadleaved species and conifers.

Despite the same site conditions, the analysis of the root system development revealed differences in root architectural characteristics among the three studied species. *Q. coccifera* plants showed the lower values in all root characteristics especially in the number of coarse, medium and fine roots. *P. brutia* root system had more second-order medium roots in relation to other two species, but almost all first-order laterals exhibited whirling. On the contrary, root system of *S. junceum* plants was more fibrous with many fine roots and third order medium roots, with longer and thicker coarse roots (outside the space of the digging hole) and with the fewer first-order whirling roots. Actually, whirling seems to be a not typical strategy for root system growth in *S. junceum* plants. This latter species root alterations are common to mechanically stressed plants whose roots are thicker and more numerous in order to ensure plant stability and survival (Goodman and Ennos, 1996). Considering its root adaptation together with higher survivorship, *S. junceum* resulted the best species candidate for eco-engineering purposes. This better adaptation of *S. junceum* is also asserted by Preti and Giadrossich (2009) who found that *S. junceum* plants showed good biomechanical characteristics with regard to slope stabilization, and where inclinations are quite steep.

Generally, the root systems of the studied species faced strong difficulties in their expansion due to the limiting soil material, and the impenetrable walls of the digging hole. Thus, most roots restricted within the digging's hole space and only few roots developed either outside the limited space of the digging holes or towards the bedrock cracks, in the direction of the lower impedance and more available water. As previously reported, roots tend to grow into the cracks under drought stress when the moisture content in cracks is higher (Li et al., 2007). Take into account the Mediterranean climatic conditions and the adverse conditions of the steep soil-denuded slopes, the capacity of underlying bedrock to hold some water is crucial for the survival of any woody vegetation (Rose et al., 2003). Therefore obtaining root access to the water stored in the weathered bedrock via cracks is probably essential for establishment and survival of many species (Poot and Lambers, 2008). Li et al. (2007) found that the properties of the bedrock (such as the weathering degree) of rocky slopes affect the distribution and the anchorage resistance of the *V. negundo* root system.

In this study, almost all the roots penetrated and anchored in the bedrock cracks were coarse and medium roots. These roots embedded in the bedrock cracks exhibited a deformation, especially in the areas where the cracks were narrower than the roots width. The resistance force from the cracks resulted in a specific deformation: flat-shaped roots instead of circular. The extremity of these habitats favoured the development of such root phenotype which similarly has been reported by Li et al. (2007). This was more evident in case of *Q. coccifera* which exhibited embedded roots with a more extreme flat shape in order to penetrate deeper layers than embedded roots *P. brutia* and *S. junceum.*

According to the laboratory analysis, root tensile breaking force greatly differed among the studied species and within the species varied by root diameter class and increased with increasing root diameter. *S. junceum* roots showed significantly greater values of tensile breaking force in all diameter classes (88 to 214 N) than the other two species. Tosi (2007) also reported for *Spartium junceum* roots that root tensile breaking force ranged between 13.7 and 1391 N, with diameter ranging between 0.65 and 9.35 mm. Similarly, Preti and Giadrossich (2009), reported for *Spartium junceum* roots that the root tensile strength (the root tensile breaking force per unit root area), increases as diameter decreases. Similar values of root tensile strength (resistance) were reported by Ali (2010) for the tropical plant species *Leucaena leucocephala*, *Acacia mangium* and *Melastoma malabathricum*.

Except the naturally occurring roadside native plants that have high potential to survive and regenerate in disturbed habitats (Prach and Pysek, 2001; Karim and Mallik, 2008), in our study the planted species showed adequate adaptation characteristics that contributed both to persist under such adverse environments, and to significantly improve road restoration. These specific adaptation responses seem to be the number of embedded roots which was constant among the three studied species. These roots penetrate the cracks and their associated fungi can contribute to weathering and enlargement of rock fractures (Schenk, 2008) by increasing the gas exchange as well as biological activities around the roots. Additionally, the rainfall and the sun exposure of the surfaced bedrock may accelerate the rate of rock weathering.

5. Conclusions

On engineered soil slopes, the root systems of the studied species faced difficulties in their expansion because they restricted within the digging's hole space. However, in each root system there were few coarse and medium roots that developed towards the bedrock cracks, in the direction of the lower impedance and more available water, most of which were ¨flat-shaped¨. These roots seem to play the main role in anchoring and successful establishment of the studied species, while this root architecture reflects adaptations that maximize species' chance of finding crevices in underlying bedrock, thereby increasing their chance of obtaining water and nutrients.

Based on the overall species performance, *S. junceum* resulted the best species candidate for eco-engineering purposes.

Acknowledgements

The authors gratefully acknowledge the two anonymous referees for their valuable comments.

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