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Root distribution in willow brush mattresses: experimental framework and preliminary findings

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Abstract. Willow brush mattresses are widely used for riverbank stabilization, but research on root distribution in soils of varying conditions remains limited following their establishment. To bridge this gap, this study developed a specially designed cultivation setup featuring a modular structure and highly controllable variable settings, along with a methodology for root distribution analysis. Preliminary results indicate that root growth over two months enhanced water retention in upper soil layers. In turn, root growth was strongly influenced by soil compaction, which was categorized as loose, medium-dense, and dense. In loose sand, roots penetrate deeper, while in medium-dense and dense sand, they are restricted to shallow layers, with maximum penetration depths of 45 cm and 30 cm, respectively. Further analysis showed that in loose sand, root mean diameter, Root Area Ratio (RAR), and dry mass remain nearly constant with depth, whereas in dense sand, these parameters decrease progressively. In contrast, medium-dense sand exhibits non-linear trends, likely due to the presence of extensive lateral fine roots. This study presents a novel laboratory methodology for willow cultivation, enabling parametric analyses to optimize the application of willow brush mattresses for sustainable riverbank stabilization. Additionally, it advances practical approaches for analyzing root distribution, addressing challenges in studying soil-root interactions under varying soil conditions.

1 Introduction

Willow brush mattresses contribute to riverbank stabilization by providing immediate mechanical protection against erosion, and reinforcing soil through root development [1]. Beyond their role in soil surface stabilization, their effectiveness largely depends on the extent to which their root systems integrate with the surrounding soil [2].

A key determinant of this integration is root distribution, which governs the extent of root-soil interaction. The Root Area Ratio (RAR), defined as the ratio of root area to the total cross-sectional area at a given soil depth, serves as a critical metric for quantifying this interaction. Root distribution is influenced by both genetic and environmental factors, including lignin and cellulose content, soil configuration, temperature, moisture availability, and seasonal variations [3]. However, despite the recognized importance of soil configuration, limited research has examined how root distribution responds to varying soil densities after the establishment of willow brush mattresses.

Several field methods exist for studying root distribution, including core-break sampling [4], trench excavation [5, 6], root extraction with hydraulic [7] or air-lance techniques [8]. While these techniques provide valuable insights, they are often invasive, leading to root damage and potentially compromising plant survival, thereby limiting their applicability for long-term studies.

To address these limitations, this study introduces a laboratory-based method for investigating root distribution using a specially designed cultivation setup that replicates the configuration of willow brush mattresses used in riverbank stabilization. This approach offers several advantages:

- Realistic representation of willow brush mattress configurations to better reflect field conditions.
- Modular design that allows for precise control of experimental variables.
- A laboratory-based, non-destructive methodology that enables repeated observations without disturbing natural ecosystems.
- Accurate spatial mapping of root distribution for detailed analysis.

By establishing a methodological framework for laboratory-based root analysis, this study aims to advance research on soil-root interactions under varying soil densities, and refine the application of willow brush mattresses for riverbank stabilization.

2 Materials and methods

2.1 Plant species

The study utilizes basket willow (*Salix viminalis* L.), a fast-growing species with an extensive root system and high adaptability to moist environments, making it widely used in riverbank stabilization and erosion control [1]. For

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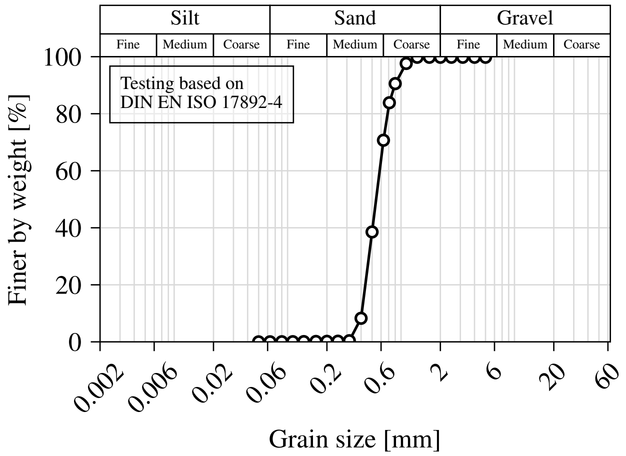


Figure 1. Grain-size distribution curve of Karlsruhe sand.

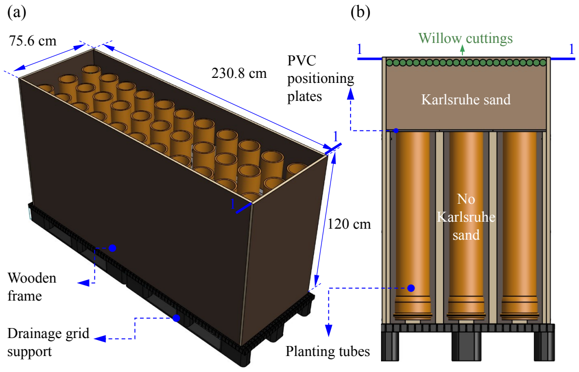
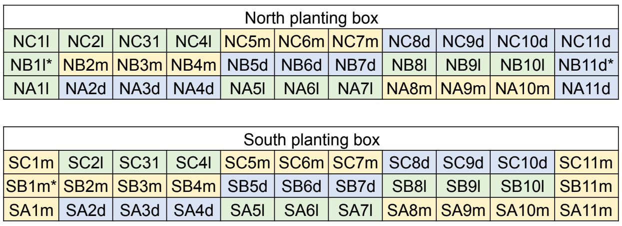


Figure 2. Schematic of the planting boxes: (a) Assembled view; (b) Sectional perspective view (1–1) after emplacement of soil and willows.



North planting box										
NC1l	NC2l	NC31	NC4l	NC5m	NC6m	NC7m	NC8d	NC9d	NC10d	NC11d
NB1l*	NB2m	NB3m	NB4m	NB5d	NB6d	NB7d	NB8l	NB9l	NB10l	NB11d*
NA1l	NA2d	NA3d	NA4d	NA5l	NA6l	NA7l	NA8m	NA9m	NA10m	NA11d

South planting box										
SC1m	SC2l	SC31	SC4l	SC5m	SC6m	SC7m	SC8d	SC9d	SC10d	SC11m
SB1m*	SB2m	SB3m	SB4m	SB5d	SB6d	SB7d	SB8l	SB9l	SB10l	SB11m
SA1m	SA2d	SA3d	SA4d	SA5l	SA6l	SA7l	SA8m	SA9m	SA10m	SA11m

Figure 3. Layout of planting tubes in the two boxes, categorized by soil compaction level: loose (green), medium-dense (yellow), and dense (blue). Soil moisture sensor locations are marked with an asterisk (*)

the plant cultivation tests, willow cuttings were sourced from Freitag Weidenart (Freising, Germany), measuring approximately 2.5 m in length with a diameter ranging from 1.5 to 2.5 cm.

2.2 Soil

Karlsruhe sand, with varying densities, was selected as the growth medium for basket willow due to its well-documented physical and mechanical properties. The sand primarily consists of subrounded quartz grains, with a mean grain size (d_{50}) of 0.55 mm and a uniformity coefficient ($C_u = d_{60}/d_{10}$) of 1.45. The minimum and maximum void ratios were determined to be 0.59 and 0.86, respectively. The grain-size distribution curve is presented in Fig. 1.

2.3 Establishment of willow brush mattresses

To statistically analyze the root distribution under various boundary conditions, two planting boxes measuring 230.8 cm in length, 75.6 cm in width, and 120 cm in height, were constructed as depicted in Fig. 2. A total of 66 tubes (KG DN 160, 152 mm internal diameter, 109 cm height), each equipped with six drainage holes (4.3 mm in diameter) at the base, were uniformly secured to the boxes with screws. Additionally, PVC positioning plates were installed 32.7 cm below the top to further stabilize the tubes and support the overlying soil. Figure 2(b) illustrates a sectional perspective view (along section line 1–1), with the right panel of the wooden frame removed to clarify the arrangement of Karlsruhe sand and willow cuttings.

For sand preparation, dense sand was compacted layer by layer, while medium-dense and loose sand were deposited using funnels of specific diameters (5.0 cm for medium-dense and 1.5 cm for loose sand) to achieve the desired soil conditions. The resulting bulk densities were classified as loose (1.40–1.47 g/cm^3), medium-dense (1.54–1.61 g/cm^3), and dense (1.63–1.64 g/cm^3), with corresponding volumetric air contents in the initial as-compacted state calculated as 44.5%–47.2%, 39.2%–41.9%, and 38.1%–38.5%, respectively. The layout of these tubes is illustrated in Fig. 3. To continuously monitor soil moisture and temperature, SMT50 sensors (Driesen+Kern, Germany) were installed at three depths within tubes NB1l, NB11d, and SB1m after calibration.

This study closely replicated the configuration of willow brush mattresses as applied in real-world riverbank stabilization projects. Following soil preparation, willow cuttings were carefully laid across the tubes, fully covering the soil surface. The initial size of cuttings was standardized by selecting specimens with stem diameters of 1.5–2.5 cm and placing 24 cuttings in each box. A thin sand layer (<1 cm) was then evenly distributed over the cuttings. Maintenance of lab-grown basket willows was planned based on Karlsruhe's climate, sand properties, and willow growth dynamics, with seasonal water demand estimated using CropWat 8.0. The irrigation regimen was structured as follows, with the reported water demand representing the total for both boxes.

- Early growth (April to May): 15 L/day to support initial development.
- Fast growth (from June): Increased to 39 L/day in June, then to 284 L/day in July to compensate for water loss due to high temperatures and sand permeability.
- Dormancy (Mid-November to March of next year): Irrigation stopped as growth nearly ceased.

Additionally, to support plant growth in the nutrient-poor sand, a mineral-based liquid fertilizer (Hauert Wuxal

Universal, Germany) was applied once per week, from late August to late September. This fertilization was initiated after the appearance of nutrient deficiency symptoms, such as leaf yellowing.

2.4 Analysis of root distribution

The rooted soil samples were collected after a 10-month growth period. Root distribution was analyzed through a systematic process involving sample extraction, cutting, imaging, and analysis. To preserve root positioning and minimize displacement, a freeze-cutting method was applied. After freezing at -20 °C for 48 h, each tube was sliced into 5 cm layers, labeled L1 to L20 from top to bottom. Following thawing, a vacuum pump was used to remove approximately 1–2 mm of the topsoil, exposing the roots for improved visibility. High-resolution images of each layer's top and bottom surfaces were then captured with a Sony Alpha 7 III camera equipped with a macro lens, under standardized lighting and composition.

Image analysis was performed using ImageJ (v1.54g, NIH, USA), and involved preprocessing, thresholding, outlier removal, and ROI management. Root morphological features, such as diameter and root area, were quantified using the 'Analyze Particles' function. The results were then exported for further analysis and visualization. Finally, the roots were extracted by sieving and washing before being fully air-dried to determine the root dry mass per layer.

3 Results and discussion

3.1 Soil moisture distribution across different densities

As shown in Fig. 4, the volumetric water content (VWC) across all soil densities exhibits a sharp increase immediately after irrigation, followed by a rapid decline to around 6%. This highlights the limited water-holding capacity of Karlsruhe sand, even in its compacted state. In addition, dense sand consistently exhibited the highest VWC at all sensor depths, while loose sand showed the lowest. This behavior is expected, as denser soils tend to retain more water at a given matric suction than the same material in a looser state, due to reduced pore sizes and increased capillarity. From June onward, VWC measured by top sensors remains consistently higher than that recorded at the bottom. This may result from improved water retention in the upper soil layers, likely influenced by root development and the interactions among roots, water, and soil.

3.2 Variation in soil density and rooted depth

Preliminary findings presented here are based on three tubes, each corresponding to a distinct soil density, as shown in Fig. 5. Compared to the initial soil density at planting, a significant change occurred only in loose sand, whereas medium-dense and dense sand remained relatively stable. In loose sand, roots could penetrate to the tube bottom, whereas in medium-dense and dense sand, root growth was confined to shallow layers, reaching depths of 45 cm and 30 cm, respectively. This pattern suggests a density-dependent constraint on root development.

3.3 Preliminary analysis of root distribution

Given the large number of samples, we initially attempted to use ImageJ's thresholding function for automatic root area identification. To assess its reliability, we compared it with manual identification. Using medium-dense sand (NA9m) as an example, preliminary results indicated that willows began developing extensive lateral fine roots from L5 (around 30 cm depth). As shown in Fig. 6, the automatic method closely matched manual results in the upper layers (L1-L5). However, in deeper layers (L6–L8), where lateral fine roots were more developed, it systematically overestimated root area. This overestimation occurred because dense lateral roots darkened local areas, causing the software to misidentify them as thicker roots. Therefore, to ensure accuracy, the preliminary results in this study were based on manual root area identification.

Root distribution was analyzed by calculating mean root diameter, RAR, and root dry mass for each layer. Figure 7 presents a comparison of these parameters across loose, medium-dense, and dense sand. In loose sand, the mean root diameter remained nearly constant at 0.5 mm across depths. A similar trend was observed for RAR and root dry mass, both showing little variation with depth. Potential edge effects at the bottom of the pipe, where root growth was laterally constrained due to limited vertical space, may have contributed to the significantly higher root dry mass observed in the bottom layer compared to other depths.

In dense sand, both RAR and root dry mass decreased progressively with depth. This pattern aligns with findings from previous studies [9–11], which attribute this decline primarily to reduced nutrient availability and restricted aeration associated with increased soil compaction.

In contrast, this trend was absent in medium-dense sand. Both RAR and root dry mass exhibited two local maxima, at approximately 20 cm and 35–40 cm depth. Notably, although RAR and root dry mass typically peak at the same depth, the maximum RAR occurred at 20 cm, whereas peak root dry mass was recorded at 40 cm. This discrepancy arises because, below 30 cm, the willows in this study developed extensive fine lateral roots, most with diameters smaller than 0.2 mm. Since RAR calculations exclude roots below this threshold, actual root biomass continues to increase at greater depths, even as RAR appears to decline. However, further investigation is needed to confirm whether these peaks are consistent across multiple replicates.

4 Future research

Further studies will build on preliminary findings to enhance statistical reliability, refine analytical approaches, and strengthen practical applications. The following areas will be prioritized:

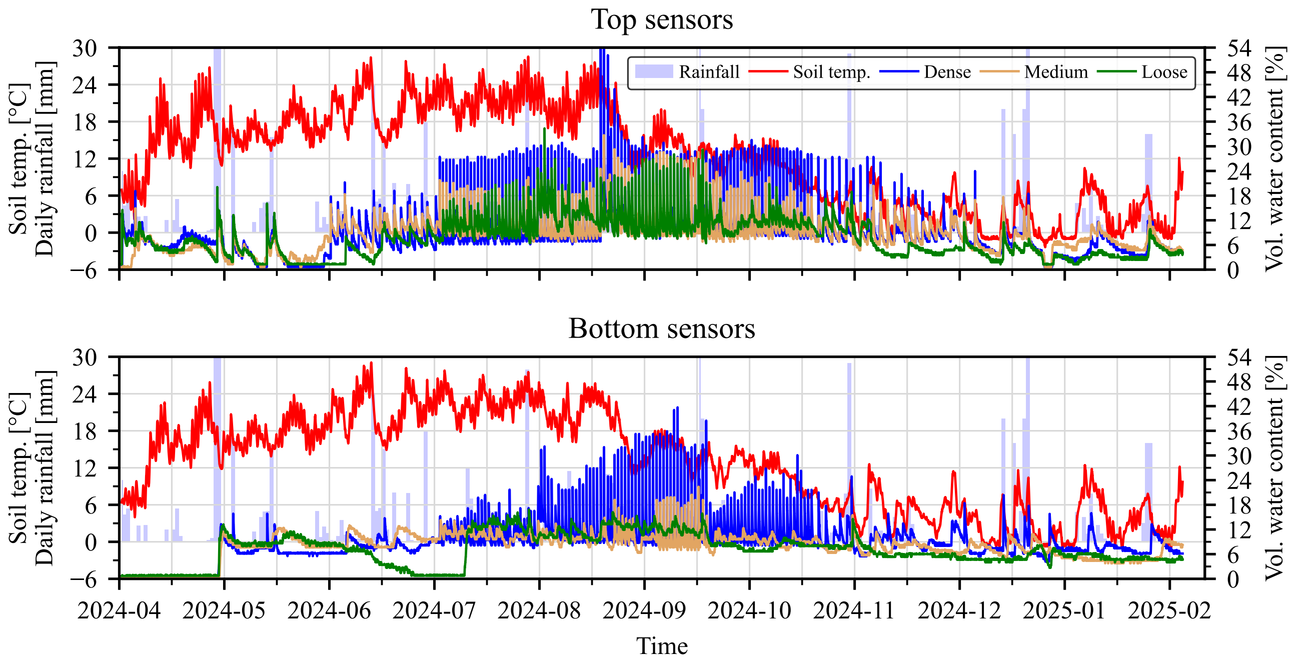


Figure 4. Variations in soil moisture and temperature based on sensor data. Daily rainfall data sourced from *https://www.imk-tro.kit.edu/*.

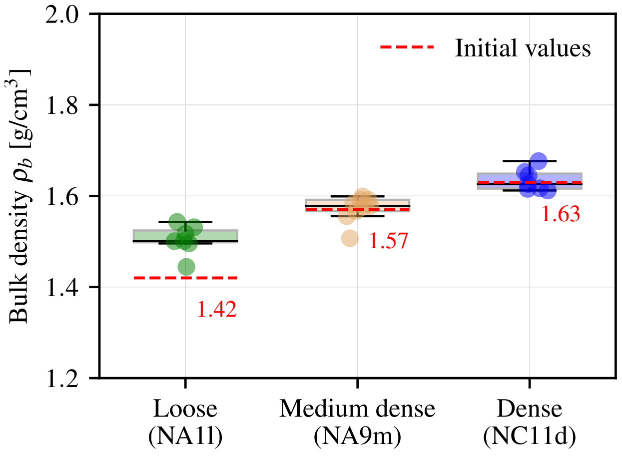


Figure 5. Comparison of bulk density across soil compaction levels

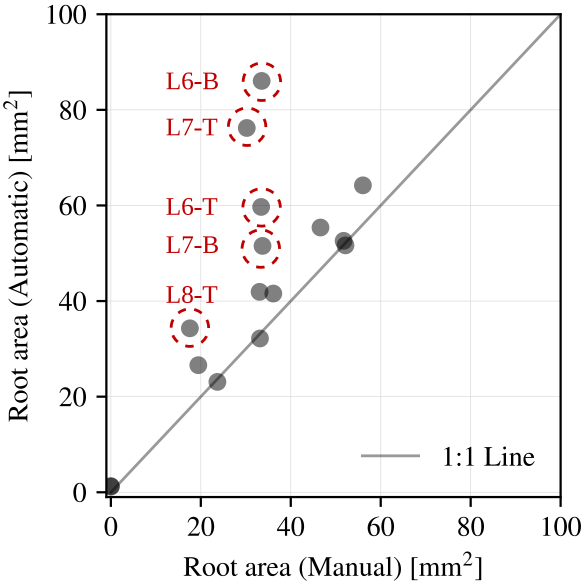


Figure 6. Comparison of automatic and manual root identification in tube NA9m. ‘T’ represents the top surface and ‘B’ represents the bottom surface of the layer.

4.1 Expanding the dataset

This study presents a preliminary analysis based on data from three experimental tubes. It focuses on a subset of observations to explore root distribution patterns across different soil densities. Future research will incorporate data from 33 tubes in the north planting box, enabling a more comprehensive assessment of root distribution across varying soil densities.

4.2 Improving automated root measurement

Accurate automatic root identification and measurement remain challenging for image-based methods, particularly in samples with extensive fine roots. Errors may result from soil particle interference, where particles resemble root color, as well as from overlapping lateral roots, which darken local areas and lead to overestimation. Future work will focus on improving the reliability and applicability of automated root quantification in complex root systems. An expanded dataset will support algorithm optimization and systematic bias correction, ultimately improving measurement precision. Regression-based adjustments will further

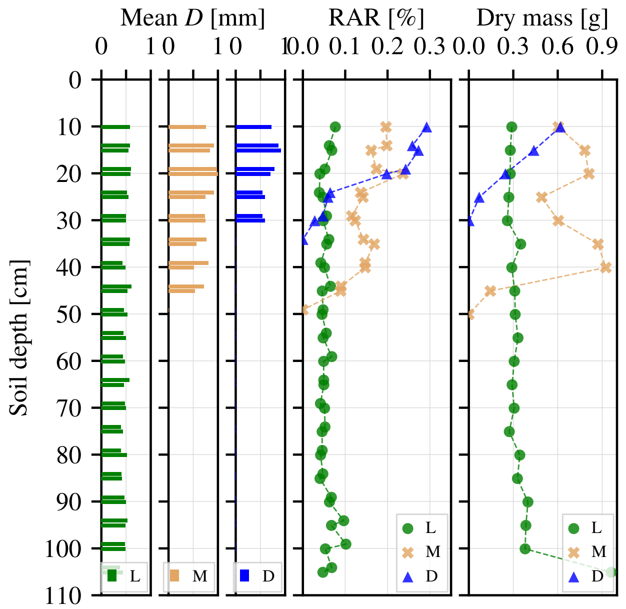


Figure 7. Soil depth profile of root distribution: mean root diameter, root area ratio, and root dry mass in tube NC11 (L), NA9m (M),and NA11d (D).

enhance accuracy by compensating for inherent measurement deviations.

4.3 Accounting for lateral fibrous roots

Root distribution studies typically focus on vertically or obliquely penetrating roots, often overlooking a large proportion of fine lateral fibrous roots. However, these fibrous roots are crucial for soil stabilization, as they form network-like structures, secrete polysaccharides, and promote soil aggregation [12, 13]. Despite their importance, image-based methods struggle to accurately quantify them in rooted soil cross-sections due to their small size and dense distribution.

Preliminary results reveal significant variations in fibrous root morphology across different soil depths, highlighting the need for a refined analytical approach to better characterize the structural relationship between taproots and fibrous roots. Future research will explore morphological skeletonization under topology-preserving constraints to characterize this relationship. By leveraging taproot characteristics, we aim to infer fine fibrous root distribution patterns, providing a more comprehensive framework for their quantification.

4.4 Optimizing practical implementation

Soil compaction influences aeration and nutrient availability, directly impacting plant productivity [14]. This study examined three soil densities and found that a high initial bulk density (>1.54 g/cm^3) maintains a stable structure with minimal variation but significantly restricts root penetration. In contrast, loose soil facilitated root penetration but may compromise soil stability. Further research is needed to optimize soil compaction to balance stability and root accessibility. This will support the refinement of strategies for implementing willow brush mattresses to enhance riverbank stability and erosion control.

5 Conclusion

This study demonstrates the feasibility of a laboratory-based method for investigating root distribution in soil, providing insights into the complex interactions between soil conditions and root development.

Sensor-captured volumetric water content (VWC) curves indicate that, over time, upper soil layers retain moisture more effectively than lower layers, likely due to root-induced modifications in soil structure. Initial findings highlight the crucial role of soil density in shaping root distribution. After a 10-month growth period, basket willow planted in loose Karlsruhe sand exhibited deep root penetration exceeding 120 cm, yet roots remained relatively fine, with consistent root mean diameter, Root Area Ratio (RAR), and dry mass across depths. In contrast, soil with an initial bulk density above 1.54 g/cm^3 remained structurally stable but significantly restricted root penetration. Dense sand exhibited a progressive decline in root-related parameters with depth, whereas medium-dense sand displayed non-linear trends, likely due to the presence of extensive lateral fine roots.

Based on these findings, future research will focus on expanding the dataset to enhance statistical reliability, refining root quantification techniques, and optimizing soil compaction strategies to achieve a balance between root penetration and soil stability in practical applications.

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References

[1] P. Fleischer, C. Gesing, O. Stelzer, geotechnik **44**, 178 (2021). 10.1002/gete.202000039
[2] A. Martinez, J. Dejong, I. Akin, et al., Géotechnique **72**, 687 (2022). 10.1680/jgeot.20.P.170
[3] M. Genet, A. Stokes, F. Salin, S.B. Mickovski, T. Fourcaud, J.F. Dumail, R. van Beek, Plant Soil **278**, 1 (2005). 10.1007/s11104-005-8768-6
[4] I. Schmid, M. Kazda, Forest Ecology and Management **159**, 37 (2002). 10.1016/S0378-1127(01)00708-3
[5] G.B. Bischetti, E.A. Chiaradia, T. Simonato, B. Speziali, B. Vitali, P. Vullo, A. Zocco, Plant Soil **278**, 11 (2005). 10.1007/s11104-005-0605-4
[6] J. Ji, N. Kokutse, M. Genet, T. Fourcaud, Z. Zhang, Catena **92**, 139 (2012). 10.1016/j.catena.2011.12.008
[7] M. Tosi, Geomorphology **87**, 268 (2007). 10.1016/j.geomorph.2006.09.019

[8] F. Danjon, D.H. Barker, M. Drexhage, A. Stokes, Ann. Bot. **101**, 1281 (2008). 10.1093/aob/mcm199

[9] G.B. Bischetti, E.A. Chiaradia, T. Simonato, B. Speziali, B. Vitali, P. Vullo, A. Zocco, Root strength and root area ratio of forest species in Lombardy (Northern Italy), in *Eco-and Ground Bio-Engineering: The Use of Vegetation to Improve Slope Stability* (Springer Netherlands, Dordrecht, 2007), Developments in Plant and Soil Sciences, pp. 31–41, ISBN 978-1-4020-5593-5

[10] J.T. Lee, M.Y. Chu, Y.S. Lin, K.N. Kung, W.C. Lin, M.J. Lee, Forests **11**, 179 (2020). 10.3390/f11020179

[11] F. Preti, F. Giadrossich, Hydrology and Earth System Sciences **13**, 1713 (2009). 10.5194/hess-13-1713-2009

[12] S. Li, Z. Wang, H.H. Stutz, Biogeotechnics **1**, 100035 (2023). 10.1016/j.bgtech.2023.100035

[13] J.L. Morel, L. Habib, S. Plantureux, A. Guckert, Plant Soil **136**, 111 (1991). 10.1007/BF02465226

[14] K.D. Montagu, J.P. Conroy, B.J. Atwell, Journal of Experimental Botany **52**, 2127 (2001). 10.1093/jexbot/52.364.2127