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RESEARCH ARTICLE

The effect of diameter and moisture content on biomechanical properties of four native Australian trees

Jiale Zhu · Abbas El-Zein · Guien Miao

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Abstract
Background and Aims Roots of plants have been shown to be effective in reinforcing soils against slope failures. Two key mechanical properties in such reinforcement are the root's tensile strength (TS) and elastic modulus (EM). However, knowledge on the combined effects of root moisture content (RMC) and root diameter on these properties is scarce. The study aims to quantify these relationships for root samples of four native Australian tree (*A. costata*, *B. integrifolia*, *E. reticulatus*, and *E. racemosa*).
Methods A series of tensile tests were conducted and the root diameter at the fracture point and RMC were measured immediately after each test. Data were analysed using both univariate and multivariate analyses.
Results Both TS and EM declined with increasing diameter. Power-law expressions were found to describe the relationship between TS and diameter moderately well, but less so the one between TS and RMC. Multivariate analyses yielded a double power-law for TS versus diameter and RMC with a stronger fit than univariate ones. A weaker power-law was found between EM and these 2 variables. Of the four trees tested, *A. costata* exhibited the highest tensile strength and elastic modulus at a 1 mm diameter, while *B. integrifolia* yielded the lowest.
Conclusion Considering both diameter and RMC as explanatory variables of TS and EM yield better accounts of experimental data. This work contributes to a better understanding of reinforcement capacity of trees generally, as well as the specific performance of roots of four native Australian trees.

Keywords Root tensile strength · Root elastic modulus · Root-soil reinforcement · Multivariate regression analysis

Introduction

Shallow landslides on hillslopes, which are often triggered by rapid rainstorms (Rickli and Graf 2009) or earthquakes (Croissant et al. 2019) and may be associated with rock falls, debris flows and foundation cavities, pose significant risks to forest ecosystems and nearby residents (Leiba 2013, Phillips et al. 2021). These shallow landslides, typically involving hillslope material less than 2 m deep and up to 1000 m^3 of soil, can manifest through sliding, flowing or more complex movements (Rickli and Graf 2009). To mitigate this, there has been a growing trend toward using vegetation to bio-engineer shallow slopes. The role of vegetation in stabilising slopes has been well-established through numerous laboratory experiments and field observa-

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Abbas El-Zein and Guien Miao contributed equally to this work.

J. Zhu (✉) · A. El-Zein · G. Miao
School of Civil Engineering, The University of Sydney, Shepherd St, 2008 Darlington, NSW, Australia
e-mail: jiale.zhu@sydney.edu.au

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tions (e.g. Preti and Giadrossich 2009; Hubble and Rutherfurd 2010; Vergani et al. 2017).

Vegetation enhances slope stability and thus supports sustainable land management. Slope stabilisation occurs via several mechanisms, including mechanically anchoring the failure plane, mitigating surface erosion, and reducing soil water content to increase soil strength (Ng et al. 2019, Schwarz et al. 2010). The literature has extensively documented the mechanical stabilisation offered by roots (e.g. Schwarz et al. 2010; Giadrossich et al. 2017; Masi et al. 2021). Specifically, robust roots vertically penetrate the basal failure plane, while lateral roots near the surface can confer additional tension or compression strength around a landslide's scarp or toe (Schwarz et al. 2010).

Several models have been proposed to predict the behaviour of root-reinforced soils, including the Wu-Waldron model (WWM) (Waldron 1977, Wu et al. 1979), the stress-step loading fibre bundle model (FBM) (Pollen and Simon 2005), the strain-step loading fibre bundle model (also referred to as the root bundle model, RBM) (Schwarz et al. 2010), and other derivative models. In these models, root tensile strength (Nilaweera and Nutalaya 1999, Operstein and Frydman 2000) and root elastic modulus (Cohen et al. 2011, Mao et al. 2018) are critical variables as they significantly influence the reinforcement behaviour.

Previous research on tensile strength and elastic modulus of roots has explored the effects of root diameter (e.g. Yang et al. 2016; Nilaweera and Nutalaya 1999; De Baets et al. 2008) and root moisture content (RMC) (Hales and Miniat 2017, Hales et al. 2013, Yang et al. 2016) as independent variables. In many studies, the tensile strength-diameter relationship is generally accepted as a power-law relationship with a larger diameter having smaller tensile strength (Bischetti et al. 2005, De Baets et al. 2008, Genet et al. 2005, Mattia et al. 2005, Nilaweera and Nutalaya 1999, Operstein and Frydman 2000, Tosi 2007, Zhang et al. 2019, 2020). A general form of the relationship is shown in the following Equation:

$$T_r(d) = k_1 d_r^{k_2} \tag{1}$$

where T_r is the tensile strength of the root in MPa, d_r is the diameter in mm, and k_1 and k_2 are species-dependent coefficients. However, this model may not be suitable for roots with diameters smaller than 1 mm as a result of structural differences between primary and secondary roots (Ng et al. 2019).

Another variable that may influence root reinforcement outcomes is RMC (Boldrin et al. 2018, Giadrossich et al. 2017, Hales and Miniat 2017, Hales et al. 2013, Yang et al. 2016, Zhang et al. 2019). However, unlike the tensile strength-diameter relationship, there is no agreed relationship between RMC and root strength. Nevertheless, it is widely recognised that roots with higher moisture content exhibit lower tensile strength. Hales and Miniat (2017) reported a 40% reduction in root tensile strength when RMC increased from a range of 20-40% to 80%-100%. Furthermore, Zhang et al. (2019) observed a linear decline in the tensile strength of herbaceous plant roots with increasing RMC. Variations in tensile strength at different RMC levels can be attributed to changes in the organic polymer strength of cell walls in response to moisture changes (Hales and Miniat 2017). However, many other studies (e.g. Fan and Chen 2010; Yusoff et al. 2016; Giadrossich et al. 2016) do not report any attempt to measure or control RMC. As Giadrossich et al. (2017) note, the absence of experimental standards might influence the applicability of results, potentially affecting the quality of root reinforcement model predictions calibrated based on the experiments. Since significant reductions in tensile strength have been observed, it is important to consider RMC when documenting tensile strength to reflect the most accurate properties for bio-engineering designs. Relying on the dry strength of roots can lead to significant overestimation of their reinforcement capabilities.

Root storage and handling may influence the biomechanical properties of roots, particularly their tensile strength, which is closely associated with RMC, lignin and cellulose degradation (Boldrin et al. 2018, Giadrossich et al. 2017). Several storage methods have been reported in previous studies, including: refrigeration (Bischetti et al. 2005, Loades et al. 2010, Mattia et al. 2005); drying roots followed by rehydration prior to testing (Genet et al. 2008, Ji et al. 2012); and storing roots in their original soil to preserve their natural moisture conditions (Cofie and Koolen 2001).

In addition to tensile strength, the elastic modulus of roots (indicative of root stiffness) is a often overlooked in tensile tests due to the primary emphasis on tensile strength as well as challenges associated with its measurement, such as the control of initial length of tortuous roots. Few studies have measured the elastic modulus of roots (e.g. Lee et al. 2020; Liang et al. 2017; Boldrin et al. 2018; Sanchez-Castillo et al. 2017; Phan et al. 2021) and the data on elastic modulus remain scarce (Schwarz et al. 2013). Additionally, calculating the elastic modulus from published results of other studies is usually not possible because the strain is not reported.

Nonetheless, the elastic modulus significantly affects the stress-strain behaviour of roots during failure, as demonstrated by Mickovski et al. (2007), and is an important parameter in displacement-driven reinforcement models, such as RBM and its derivative models (Meijer 2021). More data on elastic modulus is pivotal for root bundle models and numerical simulations that analyse strain and displacement of root-soil systems (Fan and Su 2008, Operstein and Frydman 2000). The root elastic modulus can also be influenced by various factors previously discussed. For instance, some studies (e.g. Boldrin et al. 2018; Hales et al. 2013; Phan et al. 2021), have pointed out that RMC and/or root diameter might significantly impact results. In contrast, other studies (e.g. Liang et al. 2017), suggest that such influences may not be universally applicable across all plant species.

Moreover, applying root reinforcement in specific geographical locales requires understanding of the properties of tree species indigenous to those areas. Studies have rarely reported species from Australia (Masi et al. 2021) and, at present, only limited data on the tensile strength and elastic modulus of roots from native Australian species exists (e.g. Abernethy and Rutherfurd 2001; Docker and Hubble 2008), despite the importance of these properties in root reinforcement predictive models (Mao et al. 2018).

To address these research gaps, this study reports a set of laboratory tests measuring the tensile strengths and elastic modulus of roots from four native Australian tree species, with varying root diameters and RMCs. Univariate and multivariate statistical analyses have been carried out to investigate the relationships between tensile strength, elastic modulus, diameter and RMC. In addition, the study assesses the effect of root storage on tensile strength and provides some insight into the practicality of root testing. Findings from this research adds to existing knowledge base on plant and root tensile strength, and enhance comprehension of root tensile strength to contribute to the formulation of improved constitutive root reinforcement models.

Methodology

Material used and experiment setup

Four native Australian species were selected for the research *Angophora costata* (*A. costata*), *Banksia integrifolia* (*B. integrifolia*), *Eucalyptus racemosa*(*E. racemosa*) and *Elaeocarpus reticulatus*(*E. reticulatus*). The natural distribution of these plants is shown in Fig. 1. The selected species are representative of native Australian trees found in diverse ecosystems along the east coast of Australia (Australian National Botanic Gar-

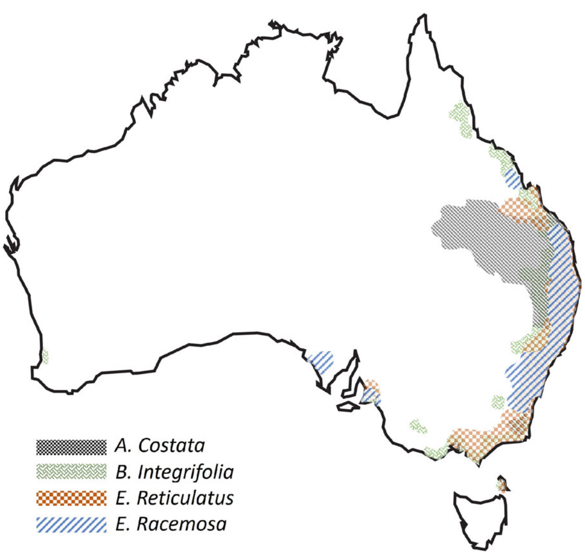

Fig. 1 Distribution map of *A. costata*, *E. racemosa*, *E. reticulatus* and *B. integrifolia*. Data collected from The Australasian Virtual Herbarium (2022) and Australian National Botanic Gardens (2016)

dens 2016, Elliot and Jones 1980, Jacobs 1955). These species were chosen for their ecological importance and potential contributions to bioengineering applications. Discussions with practitioners and horticulturists also highlighted their increasing use in urban forestry projects. For instance, *B. integrifolia* is widely recognised for its adaptability to sandy, nutrient-poor, and even saline soils, which are often unsuitable for other species (Northern Beaches Council 2019). It serves as a vital floral nectar source in heath ecosystems (Clemson 1985, Woinarski et al. 2000) and supports the preservation of threatened nomadic pollinators, playing a critical role in maintaining local ecosystem health (Eby 2016). Similarly, *E. reticulatus* produces distinctive blue berries that provide sustenance for native fauna, including the brushtail possum, the Regent Bowerbird, and various bird species, thereby enriching local biodiversity (Sharma et al. 2023). *E. racemosa* serves as an effective carbon sink, offering opportunities for environmental service payments through initiatives such as the Clean Development Mechanism of the United Nations (Noiha Noumi et al. 2018). In practical applications, *A. costata* and *E. reticulatus* have been utilised in urban disposal systems and surrounding areas to absorb effluent, reducing septic safety issues and improving environmental health (Griffith City Council 2022).

The plants were collected from Randwick City Council Nursery, a native plants nursery located in Randwick, Sydney, Australia (33°55’9.16” S, 151°13’ 28.17” E). The trees were about 12-month-old at the time of collection (April 2021) and were then transplanted into larger containers (450 mm-diameter) to reduce root decay. They were subsequently grown for an additional 18 months under consistent conditions before testing. During root sample collection, the root segments, approximately 110 mm in length, were removed from the container with some neighbouring soils placed in resealable bags to preserve the RMC. The roots were immediately placed into the bags and sealed for testing. To ensure that the root samples represented the full range of root characteristics, random sampling was employed during sample selection. Roots were randomly selected from various sections of four tree root systems per species to account for natural variability in diameter, morphology, and moisture content. Additionally, care was taken to sample from four trees of each species to further enhance the representativeness of the dataset. To achieve the low RMC that were unlikely to occur in natural plants, some root samples were air dried for up to 48 hours. Root lengths were at least 30 times the corresponding diameters following Giadrossich et al. (2017).

A material testing machine (Tinius Olsen H5KS) equipped with a specially designed clamp to increase the interface roughness was used for the tensile test. The distance between the ends of the clamps was set to 54.72±0.01 mm in the machine for the calculation of the elastic modulus. The setup for this method is depicted in Fig. 2.

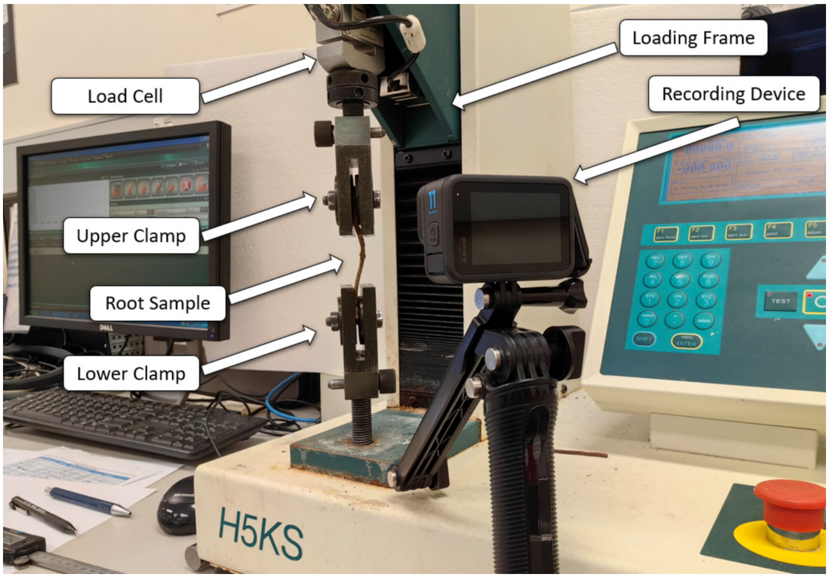

Fig. 2 The setup for the tensile test

During the experiment, the samples were loaded onto the testing machine and pulled apart at a rate of 0.5 mm/min. The tensile tests directly yielded data on ultimate load and displacement with an accuracy of 0.01 N and 0.01 mm, respectively. The root diameter and RMC were measured immediately after the tensile tests.

The root diameter was measured with a Vernier calliper with an accuracy of 0.01 mm at the fracture point. For roots with non-circular cross-sections, both the longest and shortest axes were determined, and their cross-sectional areas were approximated as ellipses. The bark's diameter was incorporated as recommended by Giadrossich et al. (2017). The RMC was determined similarly to the soil gravimetric water content, conducted by the oven-drying method for soil according to AS1289.2.1.1 (Standards Australia 2005). RMC in this study is defined by the following equation:

$$RMC = \frac{m_{weight\ of\ water}}{m_{weight\ of\ dry\ root}} \tag{2}$$

In Eq. 2, the weight of water was determined by the difference between the fresh specimen and the specimen that had been oven-dried at 105°C for 24 hours. A high-precision scale (Thermoline XA 82/220/X) with a resolution of 0.00001 g was used to determine the weight of the root samples. To prevent any water loss during transportation, the samples were sealed in tin containers, and the dry weights were measured after the containers were allowed to cool to room temperature in a drying jar containing dry silica gel. Roots, especially the fine roots, lose moisture content rapidly when exposed in air. For instance, Boldrin et al. (2018) found that approximately of 13% and 6.5% water loss in fine roots of 1 mm and 2 mm class, starting from fully saturated roots and air-dried for 30 minutes. Therefore, the tensile experiments were completed in under 5 minutes to minimise the effects of evaporation.

To explore the impact of air-drying on root storage, twenty roots of varying diameters were subjected to room temperature air-drying conditions for four weeks. Preliminary observations indicated that roots lost moisture rapidly within the first 48 hours. Based on these observations, it was assumed that the RMC stabilised after this period. The tensile strengths of roots air-dried for approximately 48 hours and four weeks were compared, and their RMC was measured to verify the RMC values were comparable.

Identification of defects and irregular morphologies

Giadrossich et al. (2017) highlighted the significance of visual analysis of specimens prior and after tensile strength testing to decide the acceptance of specimen. For instance, Mattia et al. (2005) chose only root specimens without any visible defects; whilst Ji et al. (2012), specifically selected straight root segments with no sign of damage. Rigorous visual inspection was also conducted in this study to ensure no pre-existing faults have affected the results. However, root strength can also be influenced by irregular morphologies that occur during growth, and not just damage or defects (Amoroso et al. 2010, Lindström and Rune 1999). These irregular morphologies may manifest as roots with attached soil and can be difficult to identify until the end of the experiment. Additionally, these irregular morphologies are inherent to the natural root system. As Loades et al. (2010) have found, root systems have high individual strength variability due to these natural weak points and their structures. Excluding them carries the risk of introducing bias and increasing the measured tensile strength in the root system. Therefore, the measured strength from samples with natural irregular morphologies were included in the regression analyses.

The first type of irregular morphologies in roots is a tortuous point, as shown in Fig. 3(a). This refers to a root's deviation from a straight line, which enhances the root's anchorage in the soil and facilitates nutrient absorption from neighbouring soil. Schwarz et al. (2011), emphasised the significance of these tortuous points in estimating the single root peak pull-out stress, as they contribute to additional anchorage. However, the non-axial stress imposing a bending moment at these branching points could lead to tearing failure at the tortuous point, resulting lower tensile strength.

Another type of irregular morphologies is a ball-shaped nodal joint. The joints may form due to natural damage in growth or nutrition storage in roots. The joints were difficult to identify by visual inspection, but they could be clearly identified after a tensile test when one end was pulled out from the nodal joint, leaving the skin still attached on the nodal socket. These joints resembled the fish-bead analogue used by Schwarz et al. (2011) to experimentally simulate a branching point. Figure 3(b) shows an example of a root with a ball-shaped node. The diameter around the joint was slightly larger, which resulted in lower measured stress in calculation.

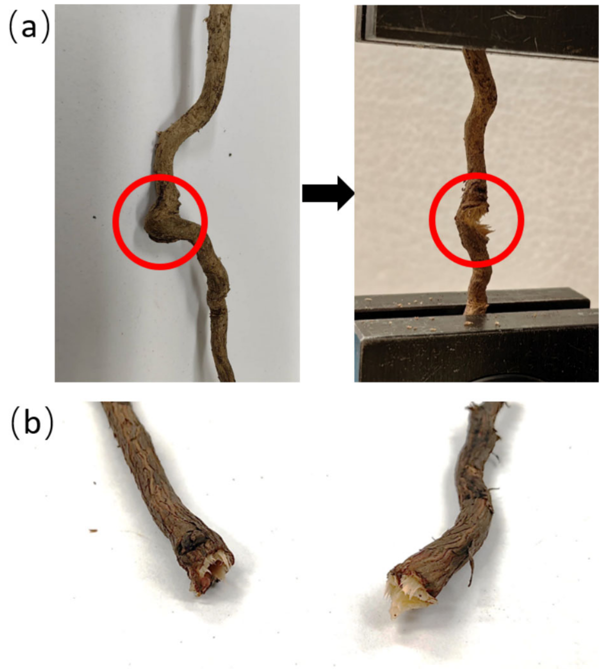

Fig. 3 Two types of observed irregular morphologies that could affect the measured tensile strength (a) tearing of a tortuous knot (b) fracture at a ball-shaped joint

Result analysis

Giadrossich et al. (2017) highlighted concerns regarding the validity of tensile test results, given the lack of standardisation. Due to their fragility, roots can be easily damaged under the compressive forces exerted by clamps, which are considerably stronger. Furthermore, since roots often taper, if a breakage happens close to the clamp, it becomes challenging to discern whether the breakage resulted from the reduced diameter or clamp-induced damage. Consequently, several studies (Abernethy and Rutherfurd 2001, Bischetti et al. 2005, Genet et al. 2008) have solely accepted outcomes from roots that fractured in their mid-section. Nonetheless, Hales et al. (2013) demonstrated that data from clamp-adjacent failures were not statistically different from mid-section failures. Additionally, Giadrossich et al. (2017) posited that discarding results from roots that broke near the clamp might lead to an overestimation of their strength. Thus, in this study, results from both the mid-section and near the clamp were considered valid, as long as no evident compression damage was observed. Using the breaking force recorded, the tensile strength was calculated by dividing this force by the cross-sectional area at the fracture point.

The elastic modulus was calculated using the following equation:

$$E = \frac{\Delta F/A}{\Delta L/L_0} \tag{3}$$

where ΔF is the change of load between the two points, ΔL is the change in displacement between the two points, A is the cross-sectional area and L_0 is the initial sample length. Note that, in the earliest phase of the experiment, the roots could not be straightened which led to under-loading. Hence, the part of the slope corresponding to this early phase was ignored in the calculation of the elastic modulus.

Analysis of results was conducted in a number of stages to quantify the relationship between, on the one hand, tensile strength, on the other hand, diameter and RMC. The procedure described below was then repeated for elastic modulus.

1. To assess the effect of root handling on results, additional linear regressions were conducted to compare differences in tensile strength of two groups of roots: i) air-dried for two days and ii) air-dried four weeks.

2. Data were initially plotted for visual assessment (tensile strength versus diameter and tensile strength versus RMC).
3. Univariate linear regressions were conducted in normal and log-log spaces and goodness-of-fit R^2 calculated. In addition, the Shapiro-Wilk (SW) test of normality was conducted on the residuals in the log-log space (with a null hypothesis that the data are normally distributed and errors of regression model are therefore stochastic, thereby lending further support to the proposed relationship).
4. Finally, based on the inspection of the univariate regressions, a multivariate regression analysis (MRA) was conducted on tensile strength, diameter, and RMC as follows.

   (a) an assessment of collinearity between diameter and RMC was performed using variance inflation factors (VIF) and Pearson's correlation coefficients (r)
   (b) 3D scatter plots were then generated to visualise the relationships between tensile strength, diameter and RMC and a suitable mathematical MRA model was determined and assessed based on goodness-of-fit R^2 values (Raju et al. 1997, Yin and Fan 2001).

Results

Effect of root storage in air-dried condition

Giadrossich et al. (2017) suggested that root storage method and storage time may affect the tensile properties. Bischetti et al. (2005) found little difference in measured root tensile strength for woody plants between various storage methods and storage times up to a few weeks. In this study, twenty roots with different diameters were stored at room temperature in sealed air-dried conditions for 4 weeks. Figure 4 presents a comparison of the testing results of roots that were air-dried for 4 weeks and for 2 days. The RMCs of the two groups were close, with an average RMC of 9.1% with SD = 2.6% for the 2-day samples, and 7.8% with SD = 2.6% for the 4-week samples.

The trend in RMC between the two groups agrees with the results reported by Boldrin et al. (2018) whereby the loss of water content reduced with time. In this study, the RMC almost reached a minimum value after 2 days of air-drying condition. The regression equation between T_s and d for the roots that were air-dried for 2 days is $T_s = 34.69d^{-0.295}$ ($R^2 = 0.40$), while the regression equation for the roots that were air-dried for 4 weeks is $T_s = 13.96d^{-0.351}$ ($R^2 = 0.43$). As illustrated in Fig. 4, although the RMCs were similar, the samples that were air-dried for 4 weeks had a much lower expected tensile strength.

The results presented in Fig. 4 agree with findings reported by Mahannopkul and Jotisankasa (2019), who studied root tensile strength in Vetiver grass under varying suction conditions. Their study demonstrated that increasing root suction (or decreasing root moisture content) typically resulted in reduced tensile strength, particularly in finer roots. This observation is consistent with the trends seen in the current study. However, the loss in tensile strength could also be due to cellulose degradation, as the samples after 4 weeks exhibited evident signs of withering and were significantly more brittle. Based on these findings, it is recommended that

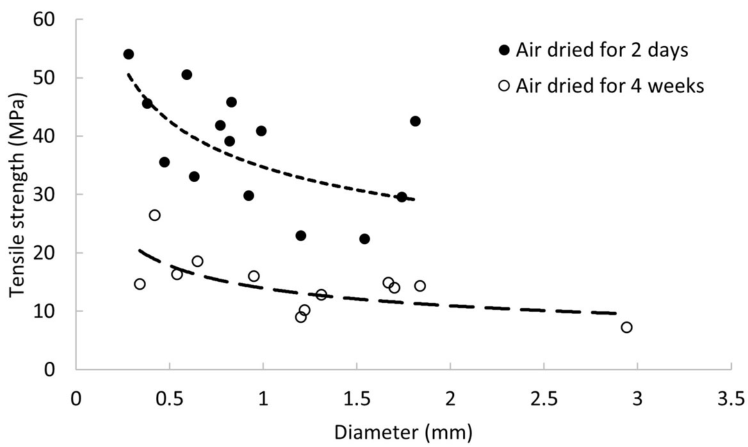

Fig. 4 Tensile strength of root samples collected from one *A. costata* and air dried for different period of times

samples should be tested promptly and should not be allowed to air-dry for extended periods to avoid the loss of cellular activity and the subsequent loss of tensile strength.

Tensile strength, diameter and RMC

A total of 308 samples were tested, resulting in 244 data points being accepted after visual inspection. 64 data points were rejected owing to non-tensile fractures, including the tearing of root cortexes. In Fig. 5, the data and power-law regression curve for each species are plotted in (a),(b),(c) and (d), showing a general trend of declining strength with increasing diameter for all species.

The regression analyses presented in Fig. 5(a), (b), (c) and (d) demonstrate the fit for the measured data points in a power-law relationship. All four R^2 values obtained show a statistically moderate relationship

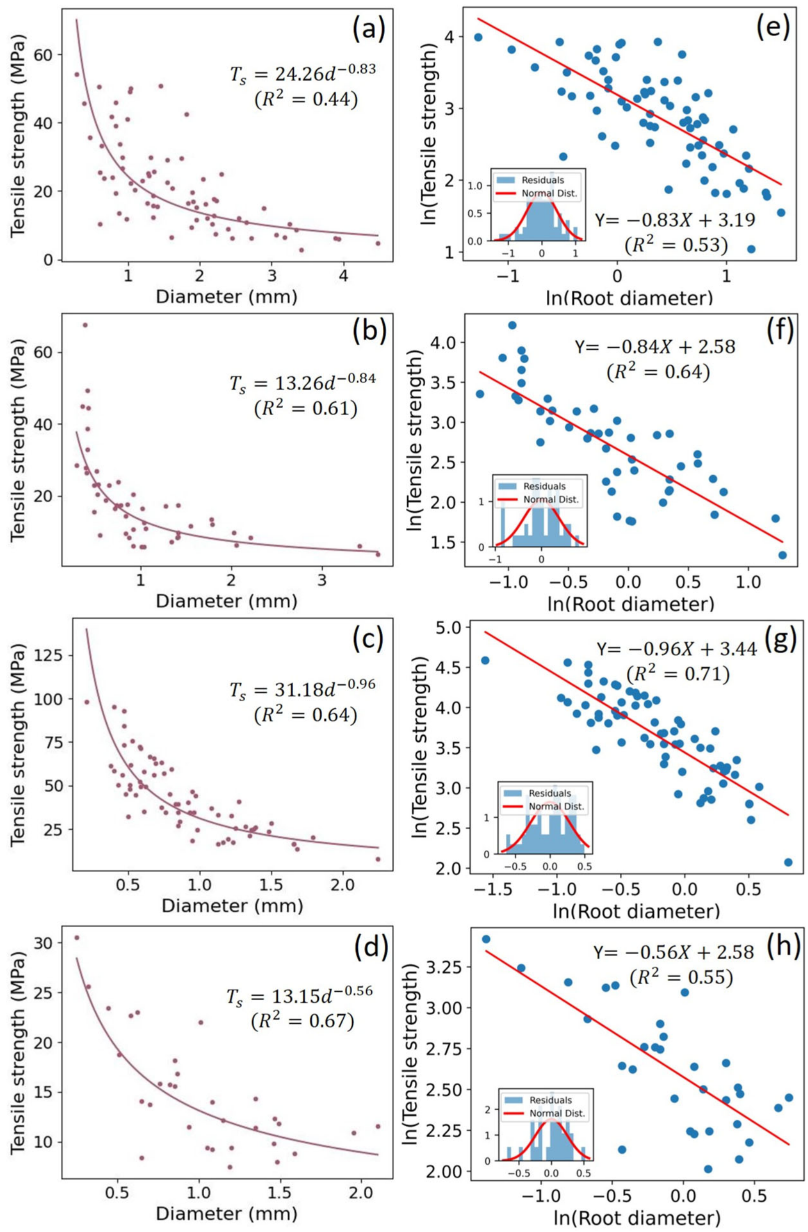

Fig. 5 Tensile strength vs diameter for (a) *A. costata*, (b) *B. integrifolia*, (c) *E. reticulatus* (d) *E. racemosa* and Linear regression of the tensile strength vs diameter in log-log space with the residual distribution for the four species in (e), (f), (g) and (h). Residuals in all 4 cases have passed the Shapiro-Wilk test for normality

between diameter and tensile strength. High R^2 values are not expected due to the inherent biological variability and stochasticity associated with living trees. Common R^2 values from literature ranges from 0.2-0.8 (e.g. Bischetti et al. 2005; Genet et al. 2005; De Baets et al. 2008; Lee et al. 2020), with most of the values falling around 0.4. Hence, the R^2 values from this study are relatively high and indicate that the power law is a reasonable approximation of the data.

The linear regression results in log-log space are shown in Fig. 5(e), (f), (g) and (h). For each of the four data sets, the relationship between the variables can be described by a linear equation in a log-log space with moderately strong relationships, adding weight to evidence provided by R^2 from the previous power-law regression. Importantly, the residuals passed the Shapiro-Wilk tests with test statistics (W) and p-values (p), suggesting that the assumption of normality was not violated (see test statistics in Table 1). Overall, these findings provide substantial evidence for a power-law relationship in the original scale for each data set.

The relationship between tensile strength and RMC was also explored. Overall, the results showed a trend whereby roots with higher RMC have lower tensile strength, consistent with the observations from Hales and Miniat (2017) and Zhang et al. (2019).

To date, to the best of the authors' knowledge, only Zhang et al. (2019) and Ekeoma et al. (2021) have quantified the relationship between RMC and tensile strength. Zhang et al. (2019) introduced the concept of relative RMC, defined as the ratio of RMC to RMC at full saturation. Their study reported a linear relationship between tensile force and relative RMC, achieving exceptionally high R^2 values of 0.999 and 0.966, although these findings were based on only four data points, representing the mean tensile forces of four test groups at varying levels of relative RMC. In contrast, Ekeoma et al. (2021) explored this relationship using negative power-law curve fitting, which revealed a weak correlation ($R^2 = 0.38$). Yang et al. (2016) approached the problem by categorising moisture content into classes and performing regression analysis, providing additional insights but without a fully quantified relationship. Boldrin et al. (2017) also discussed the potential effects of root water content on tensile strength calculations, but their work did not establish quantified relationships between RMC and tensile strength. Furthermore, the role of root water potential in influencing root tensile properties is another important aspect to consider. Studies by Jotisankasa and Taworn (2016) and Mahannopkul and Jotisankasa (2019) have shown that root suction may impacts tensile strength, with higher suction (drier roots) conditions generally leading to reduced tensile strength, particularly in finer roots. Although these findings differ from those observed in this study, they underscore the importance of root water potential as a different important parameter for understanding the biomechanical behaviour of roots and may be considered in future studies.

In this study, a linear regression model does not seem to be suitable for the data obtained in this study, with R^2 values of 0.33, 0.27, 0.03 and 0.31 for the four plants. A power-law regression model Fig. 6 yields better R^2 values of 0.59, 0.38, 0.14 and 0.44. A transformation to log-log space shown in Fig. 6 (e), (f), (g) and (h) confirms this finding, with low to moderate R^2 values. The seemingly weak relationship between tensile strength and RMC suggests that a multivariate regression analysis (MRA) may be beneficial in capturing a relationship between tensile strength, diameter and RMC.

The residuals passed the Shapiro-Wilk tests with W and p of (e) W=0.98 p=0.33, (f)W=0.98 p=0.65, (g)W=0.97 p=0.20 and (h)W=0.97 p=0.53

A model that considers both diameter and RMC was considered, and an MRA was conducted. The root samples in this study had diameters between 0.19-4.48 mm and RMC between 3.1%-300%. Prior to performing the MRA, an assessment was conducted to examine the presence of correlation between diameter and RMC. The results are presented in Table 2.

Typically, an r over 0.8 or below -0.8 indicates multicollinearity (Senaviratna and Cooray 2019) while a VIF value of 1 indicates no multicollinearity and a VIF

Table 1 Shapiro-Wilk test statistics (W) and p-values (p) for tensile strength and diameter

	A. costata	*B. integrifolia*	*E. reticulatus*	*E. racemosa*
W	0.99	0.96	0.96	0.97
p	0.77	0.16	0.06	0.45

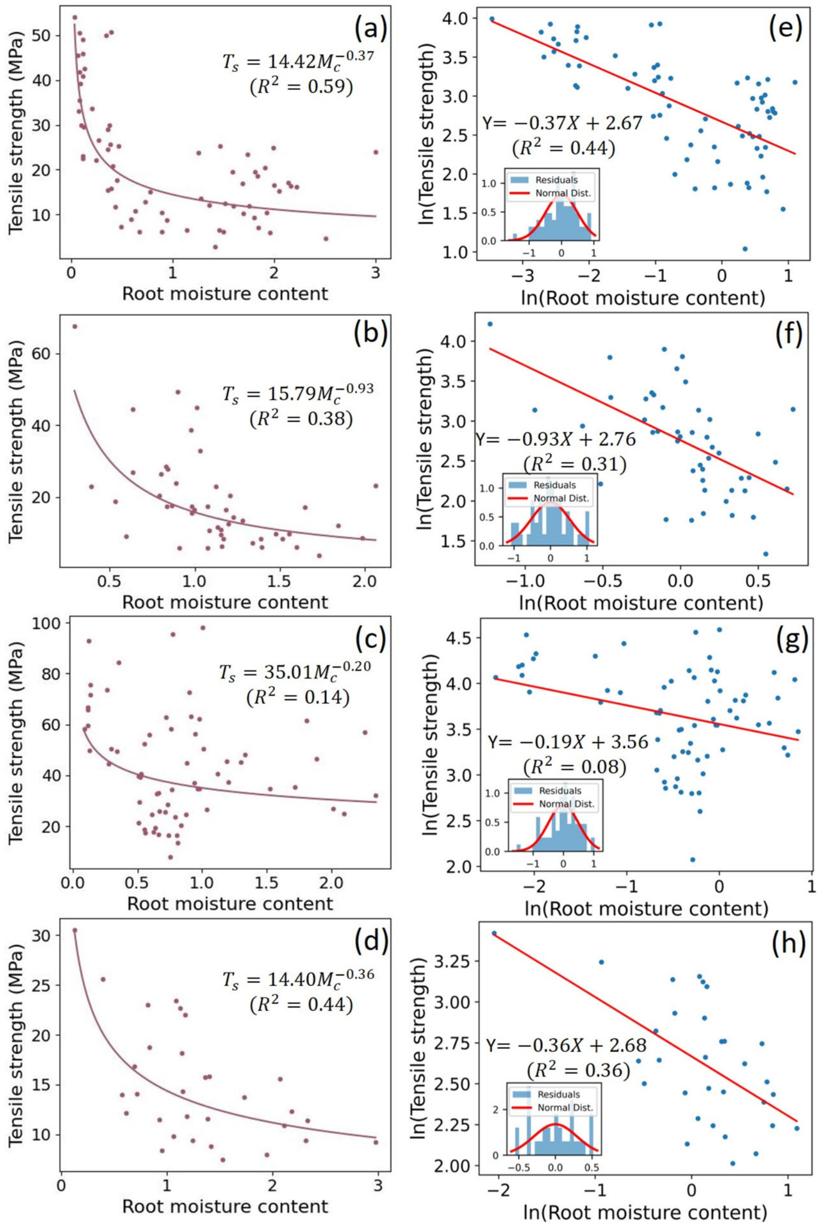

Fig. 6 Tensile strength vs root moisture content for (a) *A. costata*, (b) *B. integrifolia*, (c) *E. reticulatus* (d) *E. racemosa* and Linear regression of the tensile strength vs root moisture content in log-log space with the residual distribution for for the four species in (e), (f), (g) and (h). Residuals in all 4 cases have passed the Shapiro-Wilk test for normality

value above 5 is considered a sign of multicollinearity (Kim 2019).

The r results indicate a weak to moderate relationship between the two variables for *A. costata*, *B. inte-*

Table 2 Variance inflation factors and Pearson's correlation coefficients between root moisture content and diameter

	A. costata	*B. integrifolia*	*E. reticulatus*	*E. racemosa*
VIF	1.2	1.6	1.0	1
Covariance	0.31	0.17	-0.01	0.14
r	0.42	0.6	-0.06	0.49

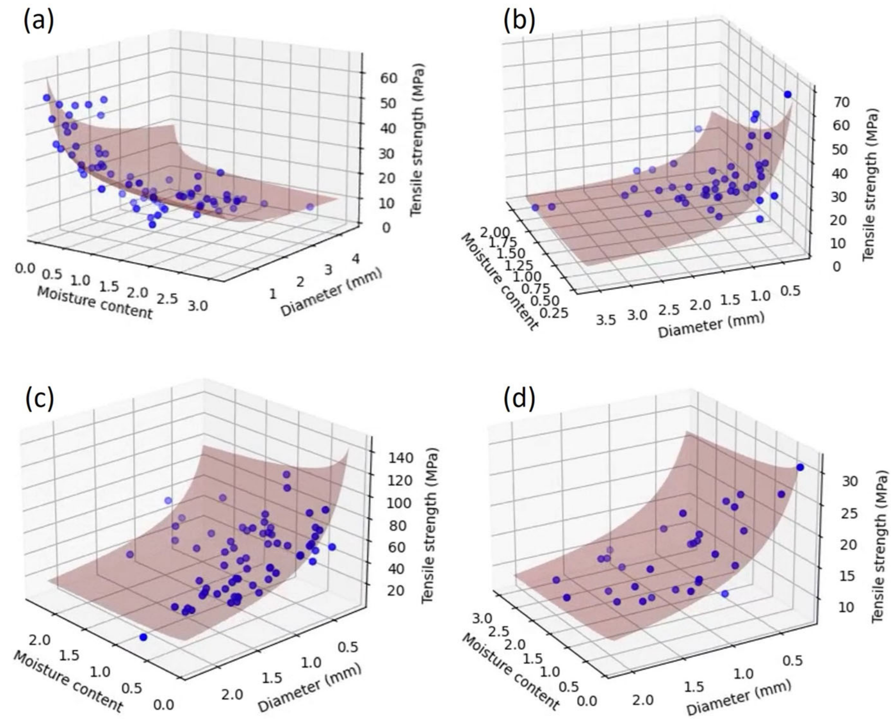

Fig. 7 3D scatter-plot of tensile strength vs root moisture content and diameter for (a) *A. costata*, (b) *B. integrifolia*, (c) *E. reticulatus* and (d) *E. racemosa*

grifolia and *E. racemosa*, and a very weak relationship for *E. reticulatus*. However, the VIF, for all species was very small. This suggests that the correlation between diameter and RMC is unlikely to be an issue for the MRA. Note however that Zhang et al. (2019) examined the correlation between the changes in RMC and diameter over time and found potential correlation between them. In this study, on the other hand, the analysis was based on instantaneous measurements of root diameter and RMC (taken immediately after the tensile tests).

As shown in Fig. 7, the relationships between the dependent variable (tensile strength) and the independent variables (diameter and RMC) are evidently non-linear.

The following power-law MRA model as shown in Equation 4 is used to fit the data:

$$T_r = k_0 \times M_c^{k_1} \times d_r^{k_2} \tag{4}$$

where k_0, k_1 and k_2 are species-dependent coefficients. The MRA results are shown in Table 3, alongside the adjusted R^2 values.

Comparing the adjusted R^2 values from the MRA (Table 3) to the R^2 values shown in Figs. 5 and 6, it is clear that the MRA model provides a better description of the relationship between tensile strength, RMC and diameter, compared to the univariate models presented earlier. As shown in Table 3, for *A. costata*, *B. integrifolia* and *E. reticulatus*, the goodness-of-fit of the MRA model is markedly better than its equivalent univariate regressions and, for *E. racemosa*, similar (diameter) or better (RMC).

Elastic modulus, diameter and RMC

The variation in elastic modulus with diameter is shown in Fig. 8(a), (b), (c), (d). The R^2 reflects weak power-

Table 3 Result of power-law multivariate regression analysis on root tensile strength against root moisture content and diameter of the four species

	k_0	k_1	k_2	Adj. R^2	$R^2_{diameter}$	R^2_{RMC}
A. costata	19.58	-0.24	-0.28	0.62	0.44	0.59
B. integrifolia	13.24	-0.38	-0.91	0.66	0.61	0.38
E. reticulatus	32.84	-0.12	-0.75	0.71	0.64	0.14
E. racemosa	13.63	-0.05	-0.53	0.66	0.67	0.44

Table 4 Shapiro-Wilk test statistics and p-values for elastic modulus and diameter

	A. costata	*B. integrifolia*	*E. reticulatus*	*E. racemosa*
W	0.93	0.97	0.98	0.97
p	0.06	0.27	0.29	0.47

law relationships between elastic modulus and diameter for *A. costata*, *E. racemosa*, and moderate relationships for *B. integrifolia*, *E. reticulatus*.

This low regression performance may arise from the sensitivity of R^2 to outliers, which could lead to a lower value if extreme data points are present. These out-

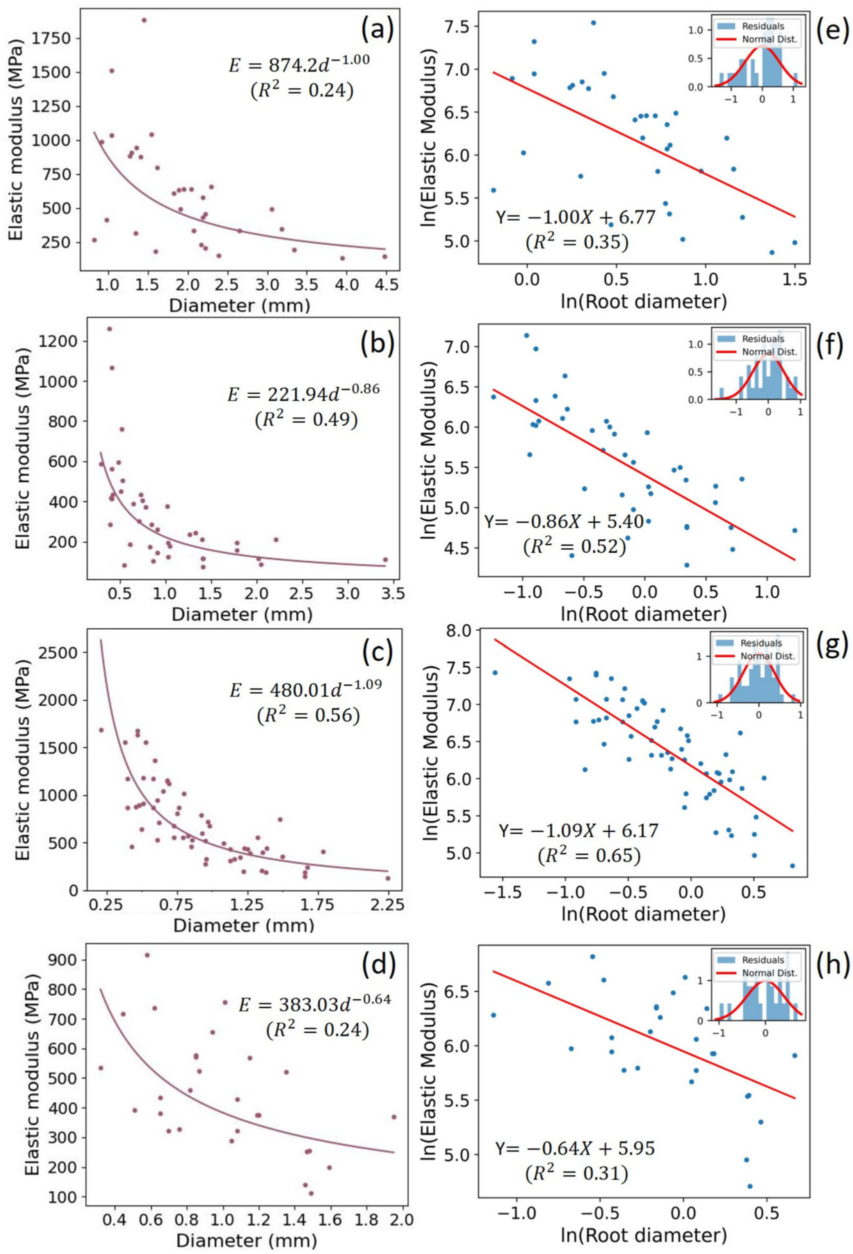

Fig. 8 Elastic modulus vs diameter for (a) *A. costata*, (b) *B. integrifolia*, (c) *E. reticulatus* (d) *E. racemosa* and Linear regression of elastic modulus vs diameter in log-log space with the residual distribution for the four species in (e), (f), (g) and (h). Residuals in all 4 cases have passed the Shapiro-Wilk test for normality

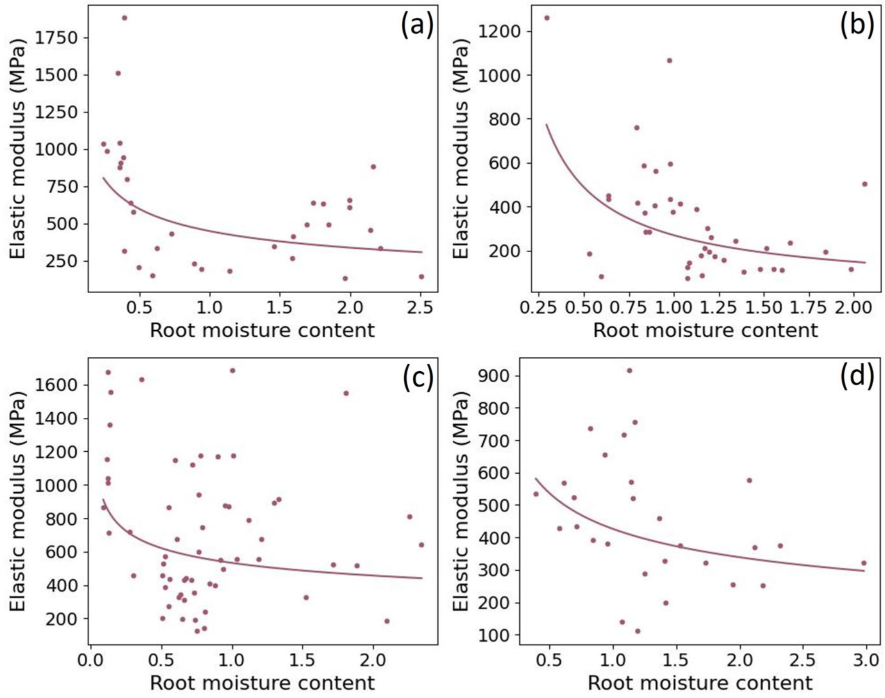

Fig. 9 Elastic modulus vs root moisture content for (a) *A. costata* R^2=0.30, (b) *B. integrifolia* R^2=0.36, (c) *E. reticulatus* R^2=0.12 and (d) *E. racemosa* R^2=0.11

liers can be identified in Fig. 8. An attempt to remove four outliers in each group of data shows an significant increase of R^2 values in *A. costata* (0.24 to 0.47), *B. integrifolia* (0.49 to 0.64) and *E. reticulatus* (0.56 to 0.60).

The elastic modulus-diameter data was also transformed into log-log space, as depicted in Fig. 8 (e), (f), (g) and (h). The regression in the transformed space is consistent with the findings from the previous R^2 values. The residuals passed the Shapiro-Wilk tests with test statistics shown in Table 4. Overall, a general power-law pattern was identifiable between elastic modulus and diameter, despite the low regression performance. Employing a larger dataset may increase confidence in these findings.

Elastic modulus versus RMC are presented in Fig. 9. The R^2 values indicate a weak relationship, particularly in the cases of *E. reticulatus* and *E. racemosa*.

Using a similar expression as Eq. 4 and conducting an MRA analysis, the elastic modulus can be expressed with the following equation

$$E = k_3 \times M_c^{k_4} \times d_r^{k_5} \tag{5}$$

The coefficients of the bivariate expression as well as the adjusted R^2 are shown in Table 5.

Table 5 demonstrates that the adjusted R^2 values obtained from MRA exhibited improvement over those from univariate analyses for *A. costata*, *B. integrifolia*, *E. reticulatus*, and of elastic modulus-RMC relation-

Table 5 Result of power-law multivariate regression analysis on elastic modulus against root moisture content and diameter of the four species

	k_3	k_4	k_5	Adj. R^2	$R^2_{diameter}$	R^2_{RMC}
A. costata	727.5	-0.36	-0.58	0.38	0.24	0.30
B. integrifolia	239.9	-0.49	-0.83	0.53	0.49	0.36
E. reticulatus	535.8	-0.12	-0.81	0.63	0.56	0.12
E. racemosa	427.0	-0.03	-0.44	0.20	0.24	0.11

ships for *E. racemosa*. However, the explanatory power of multivariate model remains low, especially for *A. costata* and *E. racemosa*.

Discussion

The results of this study provide valuable insights into the relationships between tensile strength, diameter, and RMC in the tested species. Notably, the inclusion of 35% of roots smaller than 1 mm in diameter is particularly interesting. While Ng et al. (2019) suggested that power-law regression might not be suitable for roots finer than 1 mm, findings from this study seem to suggest that any deviations from power-law caused by finer roots are not large enough to affect overall validity of power-law under the conditions of the tests conducted here.

The coefficients of the power-law regression equation between tensile strength and diameter for the four species are shown in Fig. 5(a), (b), (c) and (d) alongside the regression curves. Previous studies have found that the values of k_1 vary between 18.4 and 100.69 and the values of k_2 between -0.46 and 1.11 (Bischetti et al. 2005, Genet et al. 2005, Nilaweera and Nutalaya 1999, Zhang et al. 2019). The values obtained for k_1 and k_2 in this study are on the lower end of the values reported in prior literature. This difference may be due to the relatively young age of the samples tested during the experiments. In previous studies (e.g. Bischetti et al. 2005; Nilaweera and Nutalaya 1999) root samples were sometimes collected from old forest.

The regression analysis between elastic modulus and diameter revealed significant variation in the R^2 values, i.e. weak to moderate power-law relationship strength. Such findings are consistent with values reported from previous studies. For instance, Liang et al. (2017) observed values ranging from 0.0027 to 0.3296; Sanchez-Castillo et al. (2017) identified values between 0.2201 and 0.4456; Boldrin et al. (2018) noted a value of 0.441; and Phan et al. (2021) reported values of 0.51 and 0.6. Additionally, the low R^2 values of elastic modulus versus RMC regression indicates a weak relationship. The weak correlation suggests that additional factors, such as chemical composition, may play a more important role in influencing the elastic modulus of tree roots. Alternative relationships or data from other tree species can be investigated in future research to provide a better understanding of the factors affecting the elastic modulus of tree roots.

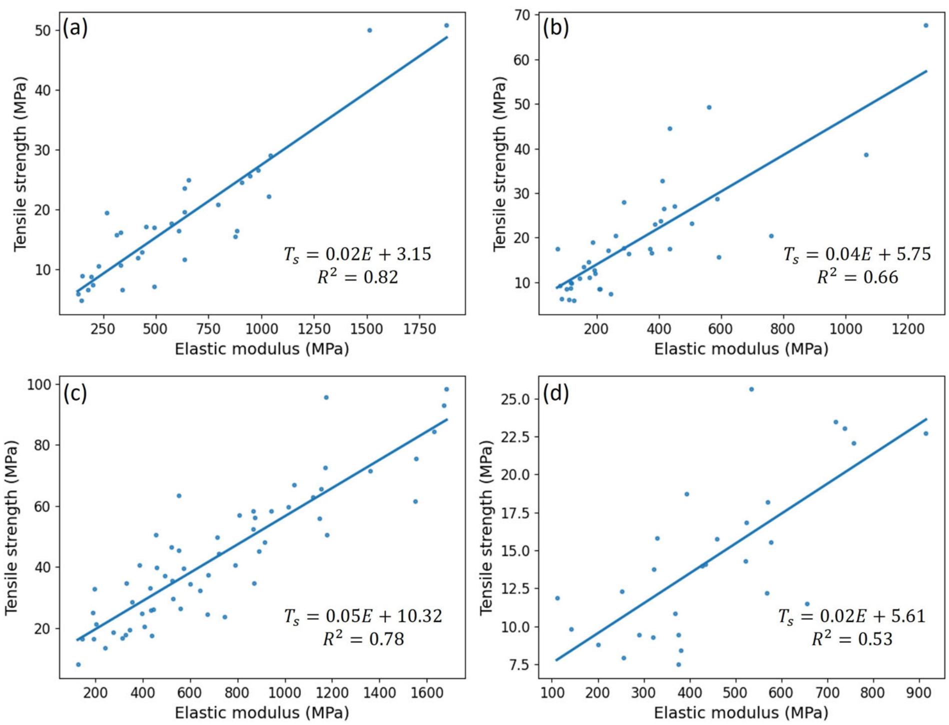

Fig. 10 Tensile strength vs elastic modulus for (a) *A. costata*, (b) *B. integrifolia*, (c) *E. reticulatus* and (d) *E. racemosa*

Tensile strength and elastic modulus of roots are critical parameters required for predicting root reinforcement solutions. The former describes the maximum stress that a root can withstand before it fractures. The latter characterises the rigidity and deformation of roots during landslides and helps in determining the sequential breakage of roots during the progressive failure described in FBMs and RBMs. In practical applications of root reinforcement, it is desirable for a species to possess fine roots with both high tensile strength and high elastic modulus. This combination allows the roots to resist deformation under stress while providing effective resistance against tensile stress (Mao et al. 2018). Figure 10 shows tensile strength versus elastic modulus for roots of the four tree species.

There is a positive correlation between tensile strength and elastic modulus for all four groups of root data, with R^2 values ranging from 0.53 to 0.82. This suggests that roots with higher tensile strength also tend to have higher elastic modulus, and hence have greater rigidity and resistance to deformation under stress. This is consistent with the findings of previous studies conducted by Lee et al. (2020), Liang et al. (2017), Phan et al. (2021), which examined a range of experimental samples including both herbaceous and woody roots.

Among the four native Australian species, *E. reticulatus* has the highest tensile strength and second highest elastic modulus at the reference diameter (taken as 1 mm). This suggests that, amongst the four species studied here, *E. reticulatus* roots may be the most suitable for shallow slope reinforcement material. However, this hypothesis requires further study, to assess the effects of root distribution and root architecture.

The findings of this study highlight two factors that could affect root tensile strength and elastic modulus, namely root diameter and root moisture content. Root tensile strength and elastic modulus are critical direct inputs in several commonly used root reinforcement models, such as the original FBM (Pollen and Simon 2005), the energy-based fibre bundle (Ji et al. 2020), and RBM with Weibull survival function (RBMw) (Schwarz et al. 2013). Accurate descriptions of these parameters significantly influence the outcomes of these models. In highly sophisticated models like RBMw, where parameters are included in power terms, inaccuracies can lead to significant deviations in predictions. Future experiments could benefit from employing fresh, saturated root samples to ensure consistency and comparability, as saturated roots yield the lowest tensile strength values, resulting in more conservative and reliable design outcomes. To improve the applicability of root reinforcement studies, standardised protocols for experiments should be developed to reduce variability across datasets (e.g. Giadrossich et al. (2017)). Additionally, standardising elastic modulus measurements is essential, as this parameter is clearly a vital input for accurate slope stabilisation models.

Conclusion

Tensile tests were conducted on roots from four native Australian tree species (*A. costata*, *B. integrifolia*, *E. reticulatus*, and *E. racemosa*). These tests suggest that a negative power-law relationships can be used to describe the behaviour between tensile strength and diameter, and a weaker negative power-law relationship was found between tensile strength and root moisture content. Hence, through a multivariate analysis, a double power-law expression was found to better predict tensile strength. A weak-moderate power-law relationship was observed between the elastic modulus and root diameter. However, little correlation was found between the elastic modulus and root moisture content. Although am MRA improved the prediction for three of the species, more data are needed to establish the relationship. Meanwhile, the effect of root storage in air-dried conditions for extensive period was explored and the results showed a significant loss of tensile strength. Accurately measuring experimental root moisture content remains challenging.

Several avenues can be pursued in future investigation of root mechanical characteristics for an improved performance estimation of bio-engineering solutions. Firstly, the dataset of plant root properties can be expanded by conducting more extensive testing including elastic modulus at different root moisture contents for the four species studied here as well as other potentially useful species. Secondly, testing on roots thicker than 4mm can be conducted. This would require a different clamping method to the one used here which could not provide enough friction for thick root without crushing them. Thirdly, different preparation methods can be explored. For example, roots can be initially dried at elevated temperatures, then re-hydrated prior to testing, or roots can be frozen at -20°C to preserve them. These drastic temperature changes might induce hysteresis in the measured tensile strength that would be reflective of behaviour on site. Fifth, root cellular activity can be measured and its effect on tensile strength quantified.

Appendix: Breaking force vs diameter

Many studies have investigated the correlation between root tensile strength and diameter. However, recent models based on fibre bundles (Pollen and Simon 2005, Schwarz et al. 2013) use a force versus diameter function as an input. In cases where force data is

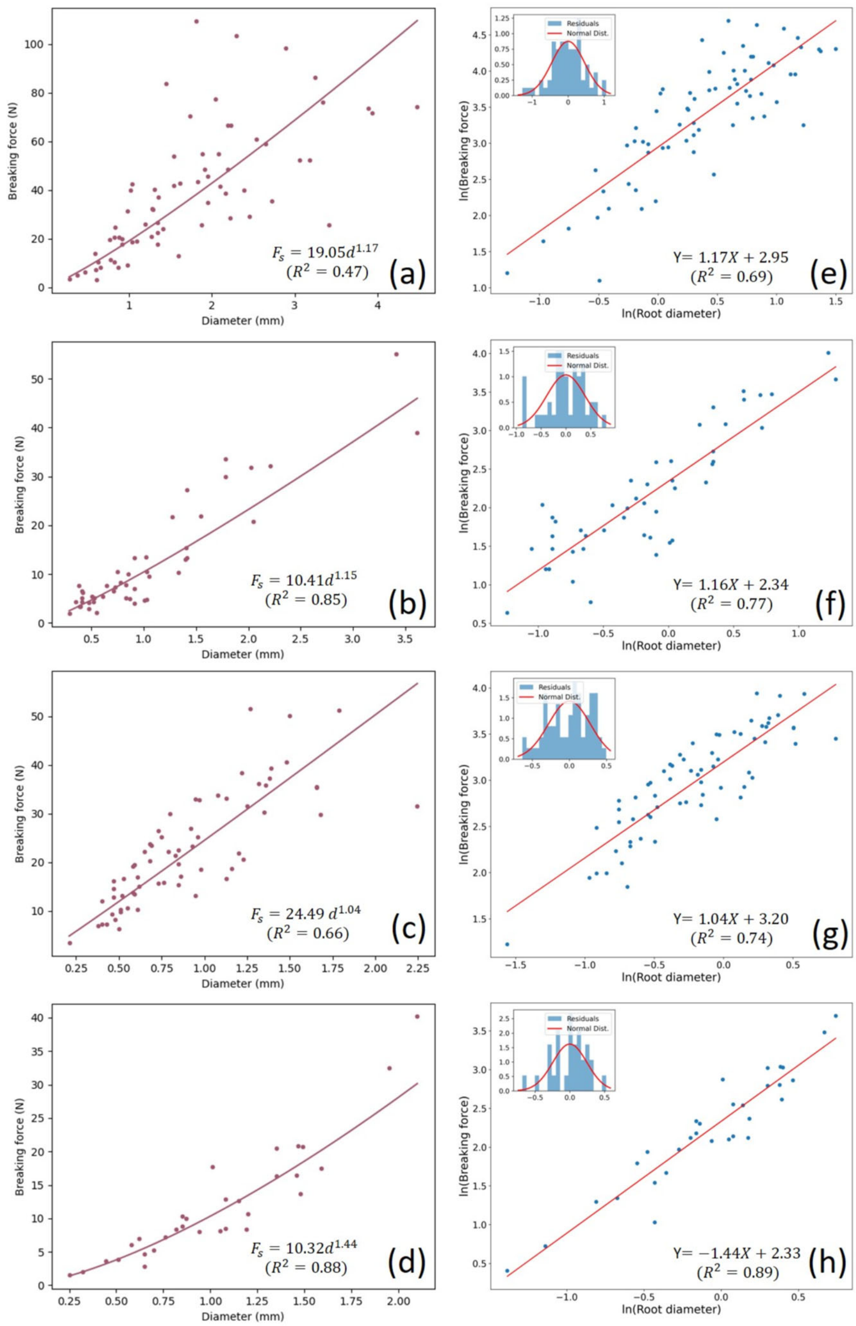

Fig. 11 Breaking force vs diameter for (a) *A. costata*, (b) *B. integrifolia*, (c) *E. reticulatus* (d) *E. racemosa* and Linear regression of the breaking force vs diameter in log-log space with the residual distribution for (e) *A. costata*, (f) *B. integrifolia*, (g) *E. reticulatus*, (h) *E. racemosa*. Residuals in all 4 cases have passed the Shapiro-Wilk test for normality

not available, tensile strength data must be converted back to force to use in these models (Giadrossich et al. 2017). Furthermore, directly transforming the power-law (or polynomial) equation from stress to force using $F = \sigma A$ will not yield the most appropriate power-law (or polynomial) coefficients (Hales et al. 2013). Therefore, presenting the results in breaking force versus diameter is also necessary. Using a similar definition of power-law relationship as demonstrated in Eq. 1, the plots as well as the values of k_1 and k_2 for breaking force vs diameter are shown in Fig. 11(a), (b), (c) and (d).

The plots showed a moderate to strong positive power-law relationship between breaking force and the diameter of the roots. For *B. integrifolia* and *E. racemosa*, the R^2 values are higher in the regression between breaking force and diameter, indicating a better fit. A regression in log-log space was also performed and the results can be seen in Fig. 11(e), (f), (g) and (h). The regression of each data set in log-log space showed a strong linear relationship and the residuals passed the normality test.

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Material Availability All data generated or analysed during this study are included in this published article. Additional datasets are available from the corresponding author on reasonable request.

Code availability Any custom computer code or algorithms used in the analysis during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest/Competing interests: The authors have no competing interests to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.

Consent for publication: The authors consent to the publication of the data and findings contained in this manuscript.

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References

Abernethy B, Rutherfurd I (2001) The Distribution and Strength of Riparian Tree Roots in Relation to Riverbank Reinforcement. Hydrological Processes 15:63–79. https://doi.org/10.1002/hyp.152

Amoroso G, Frangi P, Piatti R, et al (2010) Effect of Container Design on Plant Growth and Root Deformation of Littleleaf Linden and Field Elm. HortScience 45(12):1824–1829. https://doi.org/10.21273/HORTSCI.45.12.1824, https://journals.ashs.org/hortsci/view/journals/hortsci/45/12/article-p1824.xml, publisher: American Society for Horticultural Science Section: HortScience

Australian National Botanic Gardens (2016) Botanical Information - Australian Plant Information. https://www.anbg.gov.au/plantinfo/, publisher: Australian National Botanic Gardens, Parks Australia

Bischetti GB, Chiaradia E, Simonato T et al (2005) Root Strength and Root Area Ratio of Forest Species in Lombardy (Northern Italy). Plant Soil 278:31–41

Boldrin D, Leung AK, Bengough AG (2017) Root biomechanical properties during establishment of woody perennials. Ecological Eng 109:196–206.https://doi.org/10.1016/j.ecoleng.2017.05.002, https://www.sciencedirect.com/science/article/pii/S0925857417302550

Boldrin D, Leung AK, Bengough AG (2018) Effects of root dehydration on biomechanical properties of woody roots of Ulex europaeus. Plant Soil 431(1):347–369. https://doi.org/10.1007/s11104-018-3766-7

Clemson A (1985) Honey and pollen flora. Australian land series, Inkata Press [for] Dept. of Agriculture, New South Wales, Melbourne

Cofie P, Koolen AJ (2001) Test speed and other factors affecting the measurements of tree root properties used in soil reinforcement models. Soil Tillage Res 63(1):51–56. https://doi.org/10.1016/S0167-1987(01)00225-2, https://www.sciencedirect.com/science/article/pii/S0167198701002252

Cohen D, Schwarz M, Or D (2011) An analytical fiber bundle model for pullout mechanics of root bundles. Journal of Geophysical Research: Earth Surface 116(F3). https://doi.org/10.1029/2010JF001886, https://onlinelibrary.wiley.com/doi/abs/10.1029/2010JF001886, https://onlinelibrary.wiley.com/doi/pdf/10.1029/2010JF001886

Croissant T, Steer P, Lague D et al (2019) Seismic cycles, earthquakes, landslides and sediment fluxes: Linking tectonics to surface processes using a reduced-complexity model. Geomorphology 339:87–103. https://doi.org/10.1016/j.geomorph.2019.04.017, https://www.sciencedirect.com/science/article/pii/S0169555X19301667

De Baets S, Poesen J, Reubens B et al (2008) Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. Plant Soil 305:207–226. https://doi.org/10.1007/s11104-008-9553-0

Docker BB, Hubble TCT (2008) Quantifying root-reinforcement of river bank soils by four Australian tree species. Geomorphology 100(3):401–418. https://doi.org/10.1016/j.geomorph.2008.01.009, https://www.sciencedirect.com/science/article/pii/S0169555X08000159

Eby P (2016) Planting to conserve threatened nomadic pollinators in NSW

Ekeoma EC, Boldrin D, Loades KW et al (2021) Drying of fibrous roots strengthens the negative power relation between biomechanical properties and diameter. Plant Soil 469(1):321–334. https://doi.org/10.1007/s11104-021-05150-1

Elliot WR, Jones DL (1980) Encyclopaedia of Australian plants suitable for cultivation. Lothian Publishing Co. Pty. Ltd, Melbourne

Fan CC, Chen YW (2010) The effect of root architecture on the shearing resistance of root-permeated soils. Ecological Eng 36(6):813–826. https://doi.org/10.1016/j.ecoleng.2010.03.003

Fan CC, Su CF (2008) Role of roots in the shear strength of root-reinforced soils with high moisture content. Ecological Eng 33(2):157–166. https://doi.org/10.1016/j.ecoleng.2008.02.013, https://www.sciencedirect.com/science/article/pii/S0925857408000426

Genet M, Stokes A, Salin F et al (2005) The Influence of Cellulose Content on Tensile Strength in Tree Roots. Plant Soil 278(1):1–9. https://doi.org/10.1007/s11104-005-8768-6

Genet M, Kokutse N, Stokes A, et al (2008) Root reinforcement in plantations of Cryptomeria japonica D. Don: effect of tree age and stand structure on slope stability. Forest Ecol Manag 256(8):1517–1526. https://doi.org/10.1016/j.foreco.2008.05.050, https://www.sciencedirect.com/science/article/pii/S037811270800457X

Giadrossich F, Cohen D, Schwarz M et al (2016) Modeling bio-engineering traits of Jatropha curcas L. Ecological Eng 89:40–48. https://doi.org/10.1016/j.ecoleng.2016.01.005, https://www.sciencedirect.com/science/article/pii/S0925857416300052

Giadrossich F, Schwarz M, Cohen D et al (2017) Methods to measure the mechanical behaviour of tree roots: A review. Ecological Eng 109:256–271. https://doi.org/10.1016/j.ecoleng.2017.08.032, https://www.sciencedirect.com/science/article/pii/S0925857417305025

Griffith City Council (2022) Working Towards Safe & Responsible On-Site Sewage Management Fact Sheet 11. https://www.griffith.nsw.gov.au/get-septicsmart

Hales TC, Miniat CF (2017) Soil moisture causes dynamic adjustments to root reinforcement that reduce slope stability. Earth Surface Processes Landforms 42(5):803–813. https://doi.org/10.1002/esp.4039, https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.4039, https://onlinelibrary.wiley.com/doi/pdf/10.1002/esp.4039

Hales TC, Cole-Hawthorne C, Lovell L et al (2013) Assessing the accuracy of simple field based root strength measurements. Plant Soil 372(1):553–565. https://doi.org/10.1007/s11104-013-1765-2

Hubble TCT, Rutherfurd ID (2010) Evaluating the relative contributions of vegetation and flooding in controlling channel widening: the case of the Nepean River, southeastern Australia. Australian J Earth Sci 57(5):525–541. https://doi.org/10.1080/08120099.2010.492910, publisher: Taylor & Francis

Jacobs MR (1955) Growth habits of the Eucalypts. Commonwealth Forestry and Timber Bureau, Canberra, https://www.cabdirect.org/cabdirect/abstract/19550602567, publisher: Commonwealth Forestry and Timber Bureau

Ji J, Kokutse N, Genet M et al (2012) Effect of spatial variation of tree root characteristics on slope stability. A case study on Black Locust (Robinia pseudoacacia) and Arborvitae (Platycladus orientalis) stands on the Loess Plateau. China. CATENA 92:139–154. https://doi.org/10.1016/j.catena.2011.12.008, https://www.sciencedirect.com/science/article/pii/S0341816211002438

Ji J, Mao Z, Qu W et al (2020) Energy-based fibre bundle model algorithms to predict soil reinforcement by roots. Plant Soil 446(1):307–329. https://doi.org/10.1007/s11104-019-04327-z

Jotisankasa A, Taworn D (2016) Direct Shear Testing of Clayey Sand Reinforced With Live Stake. Geotechnical Testing J 39(4):608–623. https://doi.org/10.1520/GTJ20150217

Kim JH (2019) Multicollinearity and misleading statistical results. Korean J Anesthesiol 72(6):558–569. https://doi.org/10.4097/kja.19087, http://ekja.org/journal/view.php?doi=10.4097/kja.19087

Lee K, Chu Lin CP et al (2020) Root Traits and Biomechanical Properties of Three Tropical Pioneer Tree Species for Forest Restoration in Landslide Areas. Forests 11:179. https://doi.org/10.3390/f11020179

Leiba M (2013) Impact of landslides in Australia to December 2011. Australian J Emergency Manag 28(1)

Liang T, Bengough AG, Knappett JA et al (2017) Scaling of the reinforcement of soil slopes by living plants in a geotechnical centrifuge. Ecological Eng 109:207–227. https://doi.org/10.1016/j.ecoleng.2017.

06.067, https://www.sciencedirect.com/science/article/pii/S0925857417303956
Lindström A, Rune G (1999) Root deformation in plantations of container-grown Scots pine trees: Effects on root growth, tree stability and stem straightness. Plant Soil 217
Loades KW, Bengough AG, Bransby MF et al (2010) Planting density influence on fibrous root reinforcement of soils. Ecological Eng 36(3):276–284. https://doi.org/10.1016/j.ecoleng.2009.02.005
Mahannopkul K, Jotisankasa A (2019) Influence of root suction on tensile strength of Chrysopogon zizanioides roots and its implication on bioslope stabilization. J Mountain Sci 16(2):275–284. https://doi.org/10.1007/s11629-018-5134-8
Mao Z, Wang Y, McCormack ML et al (2018) Mechanical traits of fine roots as a function of topology and anatomy. Annals of Botany 122(7):1103–1116. https://doi.org/10.1093/aob/mcy076
Masi EB, Segoni S, Tofani V (2021) Root Reinforcement in Slope Stability Models: A Review. Geosciences 11(5):212. https://doi.org/10.3390/geosciences11050212, https://www.mdpi.com/2076-3263/11/5/212, number: 5 Publisher: Multidisciplinary Digital Publishing Institute
Mattia C, Bischetti GB, Gentile F (2005) Biotechnical Characteristics of Root Systems of Typical Mediterranean Species. Plant Soil 278:23–32. https://link.springer.com/article/10.1007/s11104-005-7930-5
Meijer GJ (2021) A generic form of fibre bundle models for root reinforcement of soil. Plant Soil 468(1):45–65. https://doi.org/10.1007/s11104-021-05039-z
Mickovski SB, Bengough AG, Bransby MF et al (2007) Material stiffness, branching pattern and soil matric potential affect the pullout resistance of model root systems. European J Soil Sci 58(6):1471–1481
Ng C, Leung A, Ni J (2019) Plant-Soil Slope Interaction. CRC Press, Boca Raton,. https://doi.org/10.1201/9781351052382
Nilaweera NS, Nutalaya P (1999) Role of tree roots in slope stabilisation. Bulletin Eng Geol Environ 57(4):337–342. https://doi.org/10.1007/s100640050056
Noiha Noumi V, Zapfack L, Hamadou MR et al (2018) Floristic diversity, carbon storage and ecological services of eucalyptus agrosystems in Cameroon. Agroforestry Syst 92(2):239–250. https://doi.org/10.1007/s10457-017-0130-5
Northern Beaches Council (2019) Native planting guide. https://www.northernbeaches.nsw.gov.au/environment/native-plants/native-planting-guide
Operstein V, Frydman S (2000) The influence of vegetation on soil strength. Proceed Institution Civil Eng - Ground Improvement 4(2):81–89. https://doi.org/10.1680/grim.2000.4.2.81, https://www.icevirtuallibrary.com/doi/10.1680/grim.2000.4.2.81, publisher: ICE Publishing
Phan TN, Likitlersuang S, Kamchoom V et al (2021) Root biomechanical properties of Chrysopogon zizanioides and Chrysopogon nemoralis for soil reinforcement and slope stabilisation. Land Degradation Development 32(16):4624–4636. https://doi.org/10.1002/ldr.4063, https://onlinelibrary.wiley.com/doi/abs/10.1002/ldr.4063, https://onlinelibrary.wiley.com/doi/pdf/10.1002/ldr.4063
Phillips C, Hales T, Smith H et al (2021) Shallow landslides and vegetation at the catchment scale: A perspective. Ecological Eng 173:106436. https://doi.org/10.1016/j.ecoleng.2021.106436, https://www.sciencedirect.com/science/article/pii/S0925857421002913
Pollen N, Simon A (2005) Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. Water Resources Res 41(7). https://doi.org/10.1029/2004WR003801, https://onlinelibrary.wiley.com/doi/abs/10.1029/2004WR003801, https://onlinelibrary.wiley.com/doi/pdf/10.1029/2004WR003801
Preti F, Giadrossich F (2009) Root reinforcement and slope bioengineering stabilization by Spanish Broom (*Spartium junceum* L.). Hydrol Earth Syst Sci 13(9):1713–1726. https://doi.org/10.5194/hess-13-1713-2009, https://hess.copernicus.org/articles/13/1713/2009/, publisher: Copernicus GmbH
Raju NS, Bilgic R, Edwards JE et al (1997) Methodology Review: Estimation of Population Validity and Cross-Validity, and the Use of Equal Weights in Prediction. Appl Psychological Measure 21(4):291–305. https://doi.org/10.1177/01466216970214001, publisher: SAGE Publications Inc
Rickli C, Graf F (2009) Effects of forests on shallow landslides - Case studies in Switzerland. Forest Snow Landscape Res 82(1):33–44
Sanchez-Castillo L, Kubota T, Silva I, et al (2017) Comparisons of the Root Mechanical Properties of three Native Mexican Tree Species for Soil Bioengineering Practices. Botanical Sci 95:259–269. https://doi.org/10.17129/botsci.802
Schwarz M, Lehmann P, Or D (2010) Quantifying lateral root reinforcement in steep slopes—From a bundle of roots to tree stand. Earth Surface Processes Landforms 35:354–367. https://doi.org/10.1002/esp.1927
Schwarz M, Cohen D, Or D (2011) Pullout tests of root analogs and natural root bundles in soil: Experiments and modeling. J Geophysical Res: Earth Surface 116(F2). https://doi.org/10.1029/2010JF001753, https://onlinelibrary.wiley.com/doi/abs/10.1029/2010JF001753, https://onlinelibrary.wiley.com/doi/pdf/10.1029/2010JF001753
Schwarz M, Giadrossich F, Cohen D (2013) Modeling root reinforcement using a root-failure Weibull survival function. Hydrol Earth Syst Sci 17(11):4367–4377. https://doi.org/10.5194/hess-17-4367-2013
Senaviratna NaMR, Cooray TMJA (2019) Diagnosing Multicollinearity of Logistic Regression Model. Asian J Probability Stat pp 1–9. https://doi.org/10.9734/ajpas/2019/v5i230132, https://journalajpas.com/index.php/AJPAS/article/view/96
Sharma S, Hussain S, Rai DV, et al (2023) A comprehensive analysis on the ecosystem services of Elaeocarpus L. (Elaeocarpaceae): a review. J Phytol pp 12–37. https://doi.org/10.25081/jp.2023.v15.8020, https://updatepublishing.com/journal/index.php/jp/article/view/8020
Standards Australia (2005) AS 1289.2.1.1-2005 Determination of the moisture content of a soil - Oven drying method (standard method). https://infostore.saiglobal.com/en-us/standards/as-1289-2-1-1-2005-128273spssaigspsasspsassps271139/
The Australasian Virtual Herbarium (2022) The Australasian Virtual Herbarium. https://avh.ala.org.au/occurrences/search?q=taxa%3A%22Eucalyptus+racemosa%22#tabspsmapView, publisher: jurisdiction:Australian Govern-

ment Departmental Consortium;corporateName:Council of Heads of Australasian Herbaria

Tosi M (2007) Root tensile strength relationships and their slope stability implications of three shrub species in the Northern Apennines (Italy). Geomorphology 87(4):268–283. https://doi.org/10.1016/j.geomorph.2006.09.019, https://www.sciencedirect.com/science/article/pii/S0169555X06004478

Vergani C, Giadrossich F, Buckley P et al (2017) Root reinforcement dynamics of European coppice woodlands and their effect on shallow landslides: A review. Earth-Sci Rev 167:88–102. https://doi.org/10.1016/j.earscirev.2017.02.002, https://www.sciencedirect.com/science/article/pii/S0012825216301611

Waldron LJ (1977) The Shear Resistance of Root-Permeated Homogeneous and Stratified Soil. Soil Sci Soc America J 41(5):843–849. https://doi.org/10.2136/sssaj1977.03615995004100050005x, https://onlinelibrary.wiley.com/doi/pdf/10.2136/sssaj1977.03615995004100050005x, https://onlinelibrary.wiley.com/doi/pdf/10.2136/sssaj1977.03615995004100050005x

Woinarski JCZ, Connors G, Franklin DC (2000) Thinking honeyeater: nectar maps for the Northern Territory, Australia. Pacific Conservation Biol 6(1):61–80. https://doi.org/10.1071/pc000061, https://www.publish.csiro.au/pc/pc000061, publisher: CSIRO PUBLISHING

Wu TH, McKinnell WP III, Swanston DN (1979) Strength of tree roots and landslides on Prince of Wales Island, Alaska. Canadian Geotechnical J 16(1):19–33. https://doi.org/10.1139/t79-003, https://cdnsciencepub.com/doi/10.1139/t79-003

Yang Y, Chen L, Li N et al (2016) Effect of Root Moisture Content and Diameter on Root Tensile Properties. PloS One 11(3):e0151791. https://doi.org/10.1371/journal.pone.0151791

Yin P, Fan X (2001) Estimating R 2 Shrinkage in Multiple Regression: A Comparison of Different Analytical Methods. J Experiment Educ 69(2):203–224. https://doi.org/10.1080/00220970109600656, publisher: Routledge

Yusoff NA, Fauzi MFM, Abdullah F (2016) The Study of Soil-Roots Strength Performance by Using Pennisetum Setaceum Grass. MATEC Web of Conferences 47:03021. https://doi.org/10.1051/matecconf/20164703021, https://www.matec-conferences.org/articles/matecconf/abs/2016/10/matecconfspsiconcees2016sps03021/matecconfspsiconcees2016sps03021.html, publisher: EDP Sciences

Zhang C, Zhou X, Jiang J et al (2019) Root moisture content influence on root tensile tests of herbaceous plants. CATENA 172:140–147. https://doi.org/10.1016/j.catena.2018.08.012, https://www.sciencedirect.com/science/article/pii/S0341816218303369

Zhang C, Liu Y, Liu P et al (2020) Untangling the influence of soil moisture on root pullout property of alfafa plant. J Arid Land. https://doi.org/10.1007/s40333-020-0017-6

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