LIVE ROOT-WOOD TENSILE STRENGTHS OF SOME COMMON NEW ZEALAND INDIGENOUS AND PLANTATION TREE SPECIES

ALEX J. WATSON
Landcare Research,
P. O. Box 69, Lincoln, Canterbury, New Zealand

and MICHAEL MARDEN
Landcare Research,
P. O. Box 445, Gisborne, New Zealand

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ABSTRACT

Roots with under-bark diameters of between 1 and 4 mm from 11 New Zealand indigenous riparian plant species — lacebark (*Hoheria sexstylosa* Col,), kowhai (*Sophora tetraptera* J.S.Mill.), manuka (*Leptospermum scoparium* J.R. et G.Forst.), fivefinger (*Pseudopanax arboreus* (Murr.) Philipson), kohuhu (*Pittosporum tenuifolium* Sol. ex Gaertn.), rewarewa (*Knightia excelsa* R.Br.), cabbage tree (*Cordyline australis* (Forst.f.) Endl.), ribbonwood (*Plagianthus regius* (Poit.) Hochr.), lemonwood (*Pittosporum eugenioides* A.Cunn), tutu (*Coriaria arborea* Lindsay), and karamu (*Coprosma robusta* Raoul) — were tested to determine their live root-wood tensile strength using a Floor Model 1195 Instron Universal Testing Machine. These results were coupled with those from earlier tests on the native tree species southern rata (*Metrosideros umbellata* Cav.), red beech (*Nothofagus fusca* (Hook.f.) Oerst.), hard beech (*N. truncata* (Colenso) Cockayne), mountain beech (*N. solandri* var. *cliffortioides* (Hook.f.) Poole), manuka, kanuka (*Kunzea ericoides* var. *ericoides* (A.Rich.) Joy Thomps.), and kamahi (*Weinmannia racemosa* L.f.), and the exotic plantation species Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and radiata pine (*Pinus radiata* D.Don) to allow a wider-ranging comparison of live root-wood tensile strengths of those trees and shrubs that can commonly be found growing in potentially unstable slope and/or riparian environments throughout New Zealand. The mean live root-wood tensile strengths of these plant species ranged from 8 to 52 MPa.

Keywords: root-wood tensile strength; soil stability.

INTRODUCTION

Trees improve soil stability through a variety of mechanisms that fall broadly into two main categories — hydrological and soil moisture modification, and mechanical soil reinforcement. The understanding of how vegetation contributes to soil stability is generally well advanced. However, the selection of plant species having specific below-ground qualities that could be utilised to enhance mechanical soil reinforcement is not as well developed. In New Zealand, plant species for erosion control are often chosen by default. Species selection is frequently decided on features such as environmental adaptability, ease of availability, commercial viability, and/or aesthetic characteristics. If root anchorage is considered, it is usually that of perceived below-ground performance based on above-ground growth characteristics, rather than on specific root-system parameters known to contribute to soil stabilisation.

Root system architecture/morphology and stand density are major factors that influence the degree to which trees enhance the mechanical reinforcement of soils (Phillips & Watson 1994). Soils containing roots have the ability to undergo larger shear displacements before reaching failure conditions than soils without roots (Ekanayake & Phillips 1999; Ekanayake *et al.* 2004). The extent to which roots improve soil stability depends not only on attributes such as root-to-soil volume and root area ratios (Wu *et al.* 1979; Abernethy & Rutherfurd 2001; Easson & Yarbrough 2002), but also on the specific root-system characteristics of the vegetation involved. Roots impart resilience to the soil, a component of which is the magnitude of the live root-wood tensile strength.

Shear stresses set up within the soil mobilise the tensile resistance of the enclosed roots. If the soil fails, roots can respond in a number of ways (Abernethy & Rutherfurd 2001):

(1) The roots may pull out. The full reinforcement potential, particularly of shallow roots, is often not realised as soil failure occurs before peak tensile strength is reached. Under these circumstances the resistance provided by the roots is supplied by the cohesion of the root-soil interface.

(2) The roots rupture at or near the shear plane. In this scenario the reinforcement provided by the root-wood tensile strength is fully utilised.

(3) The roots rupture at some point within the soil regolith. During soil failure the full reinforcement potential of the roots is realised, and after root rupture there remains some residual reinforcement as the roots are pulled through the soil.

In summary, roots provide reinforcement to soils through a combination of their tensile strength, frictional resistance, and soil bonding properties.

There is a need to quantify the root contribution to soil shear resistance. As this contribution is in part dependent on the root tensile strength of the plant species involved, a knowledge of a range of root-wood tensile strengths provides important information that is often required in root-soil assessment analysis, and can be useful when selecting plant species for erosion control.

A portion of the root tensile strength information given here was part of a programme designed to investigate the potential soil-stabilising characteristics of New Zealand indigenous plant species associated with stream bank restoration (Marden *et al.* in press). The balance was from previously published live root-wood tensile strength investigations. This allowed the pooling of a number of widely dispersed and not always readily accessible data sets, to give a single database representative of a wide range of trees and shrubs commonly found growing in potentially unstable slope and/or riparian environments throughout New Zealand.

All root-wood tensile strengths given in this manuscript were investigated using the same equipment and a single standardised testing procedure.

METHODS

Eleven New Zealand indigenous plant species commonly found in riparian areas — lacebark, kowhai, manuka, fivefinger, kohuhu, rewarewa, cabbage tree, ribbonwood, lemonwood, tutu, and karamu — were selected for a trial in which a number of their growth performance parameters were examined (Marden *et al.* in press). Live root-wood tensile strength was selected as one of these parameters (Table 1) because roots are known to contribute to soil strength (e.g., Ekanayake & Phillips 1999; Gray & Sotir 1996; Wu *et al.* 1979) and, as roots of the faster-growing plant species (softwoods) are inclined to possess less tensile strength than similar-sized roots from the slower-growing hardwood species (O'Loughlin & Ziemer 1982), their live tensile strength magnitudes tend to be species specific.

Tests of roots of between 1 and 4 mm under-bark diameter were selected from earlier live root-wood tensile strength investigations of the native tree species southern rata, kanuka (Watson *et al.* 1997), red beech, (O'Loughlin & Watson 1981), manuka (Watson & O'Loughlin 1985), kamahi (Phillips & Watson 1994), and mountain beech (unpubl. data) and the exotic tree plantation species radiata pine and Douglas fir (O'Loughlin & Watson 1979) (Table 2) to allow a wider-ranging comparison of the live root-wood tensile strengths of some of New Zealand's more common trees and shrubs (Fig. 1).

Root Sampling

Root systems were excavated using one of two methods.

- Supersonic air, delivered through an air jet nozzle (Rizzo & Gross 2000), was used to excavate the root systems of the riparian plant species (Marden *et al.* in press).
- Pressurised water was a common excavation technique (Watson *et al.* 1995) used during the earlier tensile strength investigations.

Root samples between 150 and 250 mm long were collected from the exposed root systems, sealed in plastic bags to preserve root-moisture content, and when necessary kept in cool storage until testing.

Root Tensile Strength Testing

Tensile strength testing was carried out using a Floor Model 1195 Instron Universal Testing Machine, equipped with a 5-kN maximum-capacity reversible load cell. Type 3D pneumatic-hydraulic clamps with flat non-serrated jaw faces were used to grip the root ends (O'Loughlin & Watson 1979; Watson *et al.* 1997). The root ends were clamped and a strain rate of 20 mm/min was applied until rupture occurred. The applied force required to break the root was taken as the measure of root strength. The location and form of the break were noted and the unstressed mean under-bark diameter of the root at rupture point was measured using digital callipers. Tensile strength was calculated by dividing the applied force required to break the root by the cross-sectional area of the root at its rupture point. Tests subject to slippage, or those roots that broke because of crushing at the jaw faces, were disregarded.

Generally, if root diameter (x-axis) is plotted against tensile strength (y-axis), root tensile strength decreases with increasing root diameter, i.e., a negative power function (Wu 1976; Abernethy & Rutherfurd 2001; Stokes 2002). Therefore, to enable a comparison of root tensile strengths across a number of tree species, all roots tested must fall within a predetermined diameter range. In this study an under-bark root diameter measurement of between 1 and 4 mm was selected. This diameter range was chosen because it was the largest range common to all plant species tested.

One-way analysis of variance (ANOVA) was used to investigate differences in "under-bark root diameter" and "live root-wood tensile strength" between plant species. Residuals were tested for normality and, where this assumption was violated, data were natural log transformed prior to analysis to ensure homogeneous residual variance and normality. All pairwise comparisons of means were carried out using the Bonferroni method (Hsu 1996), in which a multiple-range test was used to compare one species with groups of others. All statistical analyses were performed using GENSTAT version 6.1 (GENSTAT 2002).

RESULTS

For the plant species listed in Table 1, a pairwise comparison of the mean live root-wood tensile strengths of lacebark, kowhai, and manuka showed significantly greater (comparison-wise error rate = 0.009) magnitudes than kohuhu, fivefinger, rewarewa, cabbage tree, ribbonwood, lemonwood, tutu, and karamu. Similar analysis showed the mean live root-wood tensile strengths of kohuhu, fivefinger, rewarewa, and cabbage tree roots had significantly greater (comparison-wise error rate = 0.009) tensile strengths than those of lemonwood, tutu, and karamu. Mean live root-wood tensile strengths of all species listed in Table 1 were significantly greater (comparison-wise error rate = 0.009) than karamu.

Information listed in Tables 1 and 2 was combined to allow a graphical representation of mean live root-wood tensile strength ranking (Fig. 1). For the species in Fig. 1, a pairwise comparison of the mean live root-wood tensile strengths of rata and lacebark showed significantly greater (comparison-wise error rate = 0.0003) magnitudes than red beech, kanuka, kohuhu, kamahi, fivefinger, rewarewa, cabbage tree, mountain beech, Douglas fir, ribbonwood, radiata pine, lemonwood, tutu, and karamu. Similar analysis showed the mean live root-wood tensile strength of hard beech was significantly greater (comparison-wise error rate = 0.0003) than fivefinger, rewarewa, cabbage tree, mountain beech, Douglas fir, ribbonwood, radiata pine, lemonwood, tutu, and karamu. Mean live root-wood strength of kowhai was significantly greater (comparison-wise error rate = 0.0003) than kohuhu, kamahi, fivefinger, rewarewa, cabbage tree, mountain beech, Douglas fir, ribbonwood, radiata pine, lemonwood, tutu, and karamu. In turn, live root-wood strength of manuka was significantly greater (comparison-wise error rate = 0.0003) than rewarewa, cabbage tree, mountain beech, Douglas fir, ribbonwood, radiata pine, lemonwood, tutu, and karamu. Similarly, red beech live root-wood tensile strength was significantly greater (comparison-wise error rate = 0.0003) than that of cabbage tree, mountain beech, Douglas fir, ribbonwood, radiata pine, lemonwood, tutu, and karamu. Mean live root-wood strength of kanuka was greater (comparison-wise error rate = 0.0003) than ribbonwood, radiata pine, lemonwood, tutu, or karamu. Live root-wood strengths of kohuhu, kamahi, fivefinger, rewarewa, cabbage tree, mountain beech, and Douglas fir were significantly greater (comparison-wise error rate = 0.0003) than radiata pine, lemonwood, tutu, or karamu. The mean root-wood tensile strengths of all species shown in Fig. 1 were significantly greater (comparison-wise error rate = 0.0003) than karamu.

TABLE 1–Mean live root-wood strengths and mean 1- to 4-mm under-bark diameters at break point of 11 indigenous plant species commonly associated with stream bank restoration. The upper and lower limits represent the mean ± 1 standard error.

Common name	Tensile strength (MPa)					Under-bark root diameter (mm)					n
	Mean	Upper limit	Lower limit	Max	Min	Mean	Upper limit	Lower limit	Max	Min	
Lacebark	51.28	55.21	47.67	82.53	18.51	2.11	2.24	1.98	3.6	1.2	23
Kowhai	43.72	46.73	40.91	70.40	20.68	1.89	2.01	1.77	3.2	1.1	28
Manuka	41.71	44.96	38.69	69.63	21.84	2.50	2.63	2.37	3.6	1.8	22
Kohuhu	29.30	31.48	27.27	56.08	15.74	1.96	2.09	1.83	3.9	1.7	18
Fivefinger	28.16	30.60	25.91	42.88	18.78	2.74	2.89	2.59	3.8	1.3	52
Rewarewa	26.83	28.83	24.97	52.18	10.00	2.64	2.77	2.51	3.8	1.6	24
Cabbage tree	26.42	27.80	25.11	50.18	11.68	2.35	2.44	2.26	3.5	1.5	48
Ribbonwood	21.59	23.26	20.03	46.62	10.68	2.30	2.43	2.17	3.7	1.0	22
Lemonwood	16.44	17.66	15.30	28.81	8.87	2.77	2.90	2.64	4.0	1.6	24
Tutu	15.68	16.74	14.69	30.71	4.65	2.11	2.23	1.99	3.4	1.1	29
Karamu	8.38	9.24	7.60	15.23	4.54	2.59	2.77	2.41	3.8	1.6	13

TABLE 2–Mean live root-wood strengths and mean 1- to 4-mm under-bark diameters at break point of nine plant species measured in previous studies. The upper and lower limits represent the mean ± 1 standard error.

Common name	Tensile strength (MPa)					Under-bark root diameter (mm)					n
	Mean	Upper limit	Lower limit	Max	Min	Mean	Upper limit	Lower limit	Max	Min	
Southern rata	52.06	55.96	48.42	120.99	24.83	2.49	2.64	2.34	4.0	1.1	23
Hard beech	44.17	48.31	40.38	62.83	23.02	3.15	3.34	2.96	4.0	1.2	15
Manuka	37.44	40.33	34.77	89.93	22.03	2.66	2.81	2.51	4.0	1.5	22
Red beech	36.13	37.91	34.43	82.86	17.63	2.64	2.74	2.54	4.0	1.1	52
Kanuka	34.11	36.27	32.08	75.82	18.17	2.65	2.78	2.52	3.9	1.2	32
Kamahi	28.91	31.62	26.43	37.30	14.99	3.28	3.47	3.09	4.0	2.5	15
Mountain beech	25.90	27.89	24.05	60.26	13.24	2.87	3.02	2.72	4.0	1.2	37
Douglas fir	25.79	27.31	24.36	42.75	13.13	2.84	2.96	2.72	4.0	1.5	22
Radiata pine	17.52	18.11	16.95	34.81	8.84	3.20	3.27	3.13	4.0	1.1	110

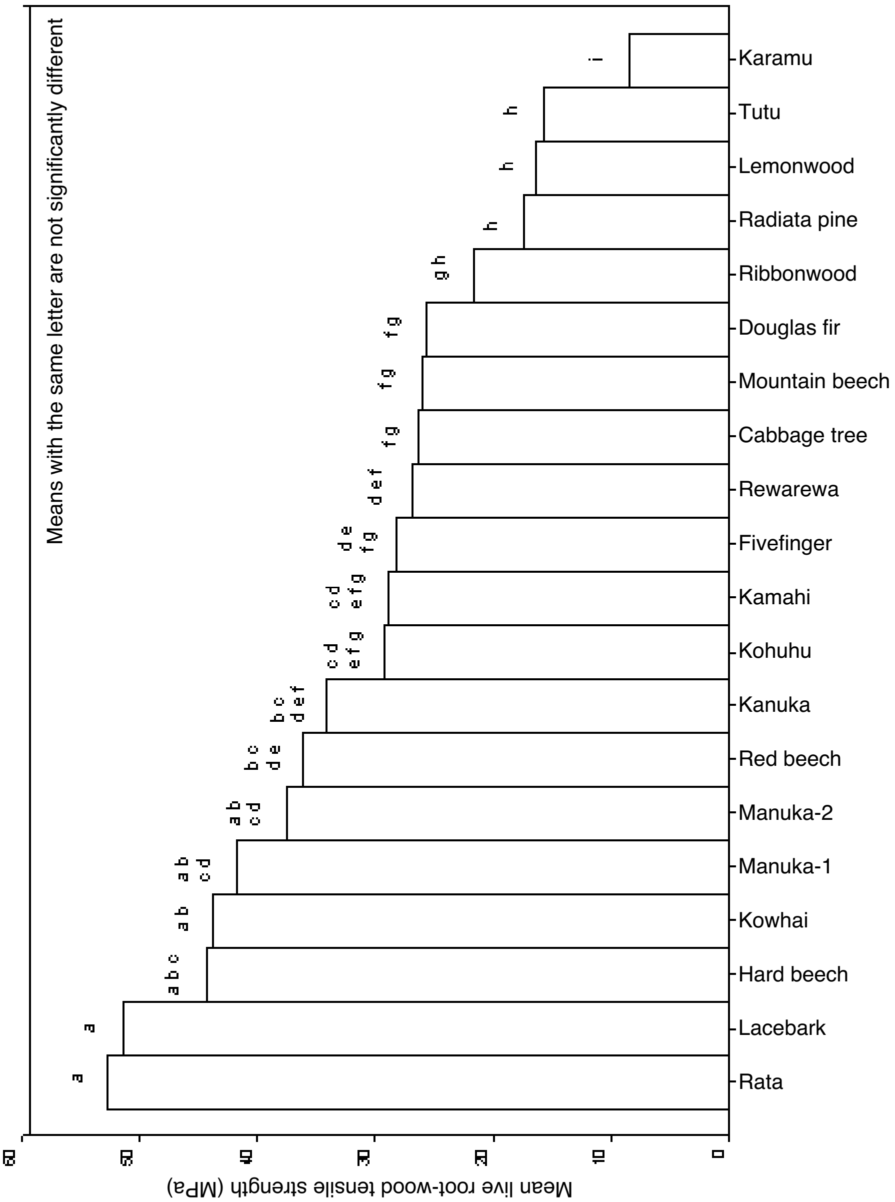

FIG. 1– Mean live root-wood tensile strengths of some common New Zealand indigenous and plantation tree and scrub species obtained from roots between 1 and 4 mm under-bark diameter.

DISCUSSION

The magnitudes of the mean tensile strength values given in Table 2 differ slightly from those values given in the referenced publications. This is due in part to the root diameter range selected being smaller than the root diameter ranges used in the earlier investigations.

Manuka was tested twice, initially in a previous study (Watson & O'Loughlin 1985) (Table 2) and in this study as a riparian species (Table 1) (*see also* Manuka-2 and Manuka-1 respectively in Fig. 1). There was no significant difference (comparison-wise error rate = 0.0003) between the mean tensile strengths of the two data sets. This would indicate uniformity in both the testing and analysis procedures, and also in the two samples tested.

The main features of root system architecture/morphology taken into account when considering root contribution to soil stability are root biomass (root system mass), root spread, rooting depth, and root distribution. The magnitudes of these are often controlled by location (e.g., geology, topography, soil type and depth, climate), stand density, and tree age. For example, a radiata pine tree growing in the deep pumice soils of the central North Island would have quite a different root architecture/morphology to a pine growing on the Canterbury Plains. Consequently, there is unlikely to be a generic root architectural/morphological description or form that can be ascribed to any one particular plant species. The above-mentioned parameters at one location are usually not transferable to another, and therefore they need to be examined at the local level. When observations are made, the site environment and conditions should be noted. It then becomes the responsibility of future investigators to ascertain whether the environment and conditions, and hence the observations and results, are applicable to their current location.

Variation in root density can be assessed using the concept of root area ratio, which has been defined as the ratio of the sum of the root areas to the area of soil profile they intersect. The root strength contribution to soil strength can be determined by multiplying the root area ratio by the mean tensile strength of the roots (e.g., Böhm 1979; Wu *et al.* 1979; Gray & Leiser 1982; Easson & Yarbrough 2002). A combination of tensile strength data and root area ratio information discriminated by, say, soil depth and/or distance from the plant stem enables a determination of the spatial distribution of soil reinforcement due to roots (Abernethy & Rutherfurd 2001). Root distribution and tensile strength measurements, coupled with soil geotechnical data, i.e., representative soil shear stress/displacement curves obtained from *in situ* direct-shear tests carried out under simulated overburden pressure and pore-water pressure conditions, can be used to compare the stability of soil with and without roots (Ekanayake & Phillips 1999; Gray & Leiser 1982).

The loss of root tensile strength with time is an important factor where trees are removed through harvesting, fire, or disease. Their root contribution to soil strength is likely to decline at a rate determined largely by the magnitude of the live root-wood tensile strength and the rate at which this strength is lost after the death of the parent tree (Watson *et al.* 1997). Therefore, given a rate of tensile strength decrease and the live root-wood tensile strength, an estimate of the time taken to loose all or part of the root reinforcement component of the soil strength can be determined. When dealing with erosion-prone sites this may be valuable information, particularly when considering a time frame of revegetation or regeneration that would allow the root-soil strength to be maintained above a critical level that would not compromise soil stability (Watson *et al.* 1999).

Root-wood tensile strength appears to decline at very similar rates (Table 3) in the New Zealand-grown species for which data are available — southern rata, kanuka (Watson *et al.* 1997), radiata pine (O'Loughlin & Watson 1979), and beech (O'Loughlin & Watson 1981). O'Loughlin & Ziemer (1982) collated a number of studies involving root-wood strength deterioration rates in Douglas fir, western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Sitka spruce (*Picea sitchensis* (Bong.) Carrière), and huckle berry (*Vaccinium parvifolium*) from the Pacific Coast Ranges of North-west America, which showed that tree roots up to 25 mm diameter lose their strength at an average of 0.3–0.5 MPa/month after tree felling.

TABLE 3–Rates of loss of root-wood tensile strength.

Common name	Loss of root-wood tensile strength (MPa/month)
Southern rata	0.45
Kanuka	0.40
Beech species	0.46
Radiata pine	0.49
Mean	0.45
Standard Deviation	0.04

If, as suggested, root-wood strength is lost at a similar rate regardless of tree species, this would indicate that the greater the magnitude of the live root-wood tensile strength, the longer the roots would take to decay to the point where soil stability would be at risk. If live root-wood strength (Tables 1 and 2) and mean rate of loss of the root-wood strength were known (Table 3), it would be possible to estimate the time available before the root-soil strength declined to a point where stability was likely to be compromised.

Root system architecture/morphology and stand density are the major factors that influence the degree to which trees enhance the reinforcement of soils. When considering such parameters as root biomass, lateral and vertical root spread, root distribution, and/or root to soil volume ratios from a soil stability standpoint, it is of little use considering root architecture/morphology without taking into account stand density. For instance, it may be true that radiata pine and Douglas fir have larger root systems than a number of indigenous species mentioned in this manuscript, but such information should be treated with some caution, as the overriding factor may well be their respective stand densities. For example, Watson *et al.* (1995) concluded that, in spite of the fact that kanuka root systems were considerably smaller than those of similar-aged radiata pine, for those critical 8–10 years after establishment naturally regenerated kanuka stands had higher root biomass per hectare and root site-occupancy rates than commercially grown pine. As can be imagined, the process of determining which is a better species for soil stability can be quite complex. It is only when this type of information has been established that root-wood tensile strength comes into play. In other words tensile strength, though important when assessing root contribution to soil strength, is just one of a mix of parameters that need to be considered for analysis for species selection during a root soil stability assessment. It would be quite erroneous to choose plant species for erosion control based solely on the magnitudes of their root tensile strengths. A number of researchers have described root-soil stability investigations — for example, Abernethy & Rutherfurd (2001), Barker *et al.* (2004), Easson & Yarbrough

(2002), Ekanayake & Phillips (1999), Gray & Leiser (1982), Gray & Sotir (1996), Wu (1976), Wu *et al*. (1979), and Wynn *et al*. (2004).

CONCLUSION

In general, the extent to which roots improve soil stability depends on the specific root-system characteristics of the vegetation under consideration. The overall efficiency of plants in reinforcing soil relies primarily on their root architecture/morphology, stand or planting density, and such parameters as the root to soil volume and root area ratios of the species concerned. Underpinning these qualities are the attributes of the individual roots, whose soil reinforcement abilities rely on their root-soil cohesion, frictional resistance, and tensile strength properties.

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