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Tree root research in New Zealand: a retrospective 'review' with emphasis on soil reinforcement for soil conservation and wind firmness

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Abstract

Background: Trees and forests have been used in New Zealand to reduce erosion, particularly from rainfall–triggered landslides, gullying, and earthflows. Most New Zealand tree root research has been conducted during the life of the New Zealand Journal of Forestry Science, with much published in it.

Methods: We undertook a retrospective 'review' of New Zealand tree root research focusing on soil reinforcement and its application for erosion control, slope stability assessment, and understanding tree stability in forests. The published and grey literature was searched using common search terms and relevant papers assessed. The international literature was not reviewed but helped provide context for the New Zealand studies.

Results: Results were aggregated into broad topic areas and key findings summarised. Where multiple studies existed for a particular species, results are presented by species. Selected data are presented to enable inter-species comparisons, and the reader is directed to additional data or the original study.

Conclusions: New Zealand tree root research has focused mostly on root description or simple measurements to support applied studies of root structure and function. Nonetheless, such research has made a valuable global contribution in addition to improving the understanding and management of New Zealand's forests. Studies show that generally, exotic species outperform indigenous species for most empirical root metrics other than root tensile strength. A combination of both lateral and vertical roots provides the best soil reinforcement and contribution to slope stability. Future research should focus on acquiring more field data and improvements in dealing with spatial and temporal variability in model development. Practical tools for land managers to target the right places with the right vegetation (species, amount, density) are a pressing need as changing climate is changing the way we manage natural hazards like landslides, floods and wildfires.

Keywords: tree roots; soil reinforcement; soil conservation; New Zealand; erosion; toppling; wind firmness, tree stability; radiata pine, mānuka, kānuka, poplar

Introduction

The New Zealand Journal of Forestry Science celebrated its 50th anniversary in 2021, and many New Zealand tree root studies have been published in this journal. Phillips & Watson (1994) reviewed New Zealand research on tree roots, including both published and unpublished studies focusing on larger (> 5 mm) structural roots. That review included both indigenous and exotic species. Since then, further New Zealand studies have involved a mix of plot- and field-based plant trials (for both indigenous and exotic species) (e.g., Marden et al. 2005) and assessment of established trees (e.g., Watson et al. 1995) (see Fig. 1 for key study locations). In recognition of the Journal's anniversary, it

FIGURE 1: Locations of key sites where root research has been conducted.

is timely to update that earlier review. This paper takes a retrospective look at New Zealand tree root research, focusing on soil reinforcement and its application for erosion control, slope stability assessment, and understanding wind firmness and tree stability in New Zealand forests. It is not intended to be a subject matter review highlighting the strengths and weaknesses of earlier work, nor does it aim to provide an in-depth assessment of New Zealand's contributions in these topics to the wider international literature. However, where appropriate and to provide context, reference to the international literature is made.

For more in-depth understanding and reviews of the topics covered in this paper, the reader is directed to: ground bioengineering techniques (Schiechtl & Stern 1996; Gray & Sotir 1996); plant root research (Smit et al. 2000; Eshel & Beeckman 2013); role of fine and coarse roots in shallow slope stability and soil erosion control (Reubens et al. 2007); how vegetation reinforces soils on slopes (Norris et al. 2008; Cohen & Schwarz 2017); root systems of woody plants (Danjon et al. 2013); wind effects on trees (Gardiner & Quine 2000; Moore & Gardiner 2001; Martin & Ogden 2006; Moore et al. 2008; Gardiner et al. 2016; Gardiner 2021); assessing 3D root architecture (Danjon & Reubens 2008); ecological mitigation of hillslope instability (Stokes et al. 2014); root reinforcement in slope stability models (Masi et al. 2021); root reinforcement dynamics and their effect on shallow landslides (Vergani et al. 2017; Rickli et al. 2019); methods to measure the mechanical behaviour of tree roots (Giadrossich et al. 2017); nature-based solutions including forests and natural hazards (Sakals et al. 2006; de Jesús Arce-Mojica et al. 2019); and ecosystem-based disaster risk reduction (DRR) (Dorren & Moos 2022).

Trees and forests are used in New Zealand to reduce erosion, particularly from rainfall-triggered landslides, gullying and earthflows, allowing pastoral agriculture to exist in erosion-prone hill country. New Zealand's forests largely consist of either harvested and managed exotic plantations or indigenous forests managed for conservation values. The latter are generally not harvested as many are within national parks or reserves, though there are small areas of privately-owned indigenous forest used for highly-regulated wood production. Increasing areas of planted forest or regenerating shrubland are being managed to generate carbon incomes, including within farms. Historically, the erosion mitigation value of forests was largely "known" in gross terms, especially from overseas experience and or from observation of New Zealand's landscapes responses to erosion events, e.g., cyclonic storms and earthquakes. This experience has shown that under similar climate and geomorphic conditions, forest-covered lands have fewer landslides generated in significant rain events and generally produce less sediment to streams and rivers than other vegetation covers such as pasture or scrub (e.g., Marden & Rowan 1993). In the late 1960s increasing stream channel erosion in forested northern Urewera was attributed to introduced deer and possums converting 'scrub hardwood forest' to less-palatable grass and fern (Wallis and James 1972). Research to understand how trees and forests achieve this largely did not get underway in New Zealand until the 1970s (O'Loughlin 1974; O'Loughlin & Watson 1979). Ironically, many of these early studies were focused on understanding what happened when trees were removed (cleared, harvested, burnt or windthrown) rather than on understanding how tree roots reinforce soils and how trees and forests mitigate against soil erosion.

Roots reinforce the soil (or media they are growing in), provide stability to the above-ground parts of a tree, and are the predominant pathway through which nutrients and moisture are carried upwards. The arrangement (architecture, shape/morphology, root length, root depth) and growth of roots are important for tree growth and survival. As mentioned above, it has long been recognised and well established in the wider literature that vegetation/trees increase the stability of a slope. They do this through several mechanisms (Greenway 1987; Rickli et al. 2019; Masi et al. 2021). In general terms, vegetation influences slope stability through either hydrological or mechanical mechanisms. The hydrological effects of interception, suction, evapotranspiration and infiltration strongly affect the soil water budget and runoff processes. The main hydrological effect of vegetation is delaying the soil from reaching the critical saturation level, triggering mass movements by several processes. The mechanical factors (soil reinforcement (increases the shear strength of soils), surcharge or weight (generally regarded as negligible for slope stability), buttressing, and anchoring) arise from the physical interactions of either the canopy (e.g., wind effects) or root system of the plant with the slope, and the soil on that slope (Greenway 1987). Roots are relatively strong in tension and weak in compression, whereas soil is relatively weak in tension and strong in compression. Together, the soil and roots form a reinforced matrix in which stress is transferred to the roots during loading, increasing the overall strength of the soil matrix that resists shear failure (Thornes 1990), similar to reinforcement of concrete structures by steel or fibreglass. The strength of root-reinforced soil thus depends on soil strength, root strength, and the strength of the bonds between soil and roots. Roots can also anchor superficial soil layers to more stable substrates or bedrock, increasing the resistance against potential failure.

Quantifying the reinforcing effects of tree roots within soils and the evaluation of hillslope stability using geomechanical and numerical models, many of which underpin tools and guidelines for land managers, relies on a realistic representation of the characteristics of tree root distribution within the hillslope and the mechanical strength of those roots (Giadrossich et al. 2017). The magnitude of reinforcement provided by roots at a particular point in the soil is dependent on several variables. These include root density, root tensile strength, the number of roots crossing potential shear planes (root area ratio), root length/diameter ratio, soil–root bond strength, root tortuosity or root straightness, and orientation of roots relative to the direction of principal strain (Wu et al. 1979; Waldron & Dakessian 1981; Greenway 1987; Simon & Collison 2002; Pollen–Bankhead & Simon 2009; Masi et al. 2021). The elastic (Young's) moduli of the roots, antecedent soil and root moistures, and frictional forces between the soil and roots are also important in quantifying root reinforcement (Pollen 2007; Fan & Su 2008).

As indicated above, this paper is not intended to be an exhaustive review summarising data from all New Zealand studies. Where appropriate, the reader is directed to the original papers for more detail. This paper has a similar structure to the review of Phillips & Watson (1994). Methods used to study tree roots in New Zealand are outlined first, then results are presented for both indigenous and exotic species (Note: common names are used in the text – see Table 1 for common and Latin names of plant species). Emphasis is on soil reinforcement and its application for erosion control, slope stability assessment, and understanding wind firmness in trees and forests. We also provide a brief commentary on future research directions.

Methods

A web-based search and the authors' knowledge of previous New Zealand studies provided the basis for this retrospective 'review'. Published literature (journal articles, books, reports, theses) including accessible grey literature (reports, file notes) on tree root research related to soil reinforcement, slope stability assessment, wind firmness and tree stability in New Zealand was assessed. Search terms in Web of Science included New Zealand, tree root(s), soil reinforcement, slope stability, toppling, wind firmness, tree stability, and tensile strength. Some information may not have been captured, e.g., from forest research/industry cooperatives and recent industry government-funded initiatives such as the Primary Growth Partnership (both funding schemes that joined researchers and industry), as these were largely confidential or not publicly accessible. There is also likely to be root information within related plant studies (e.g., pot trials to assess plant nutrition, laboratory physiology studies, seedling development, carbon turnover, propagation techniques, and establishment/management guidelines for specific species) that this review has not covered (e.g., Hinds & Reed 1957; Beets 1980; Pollock 1986; Bergin & Steward 2004). Further, publications that involved studies assessing fine roots for nutrition (Comerford et al. 1994), carbon sequestration (Hollinger et al. 1993), root propagation of seedlings and cuttings (e.g., Sutton 1980; Balneaves et al. 1992), or other purposes are not included.

Results are reported under broad topics rather than by species, except where there are several New Zealand studies for a particular species and therefore more is known. For each topic, a brief overview (often with reference to the wider literature) is followed by a summary and discussion of results from the New Zealand studies. Where appropriate, key differences between species examined in those New Zealand studies are highlighted following a similar format to the root bulletin of Phillips & Watson (1994). Other than documenting the results and general conclusions from the New Zealand studies, we do not attempt to examine the veracity of the results, i.e., in a statistical sense, or necessarily place them in the context of the international literature, but merely report them.

Results

Root research methods

Root architecture and morphology

To study tree roots, they must be exposed or released from the soil, i.e., excavated or dug up. There are some non–invasive/extractive methods (e.g., ground penetrating radar) that have been tried and reported on (e.g., Hruska et al. 1999; Butnor et al. 2003; Guo et al. 2013; Borden et al. 2017), but these are not widely used in the root research community (nor in New Zealand) as the resolution and level of detail they provide is largely limited to very large structural roots and certain soil types. Root system extraction and root measurement methods for New Zealand studies have largely followed well–established international procedures (e.g., Bohm 1979, Watson et al. 1999; Marden et al. 2005; Czernin & Phillips 2005; Giadrossich et al. 2017). Tree roots are either manually exposed (like an archaeological dig) or sluiced with high-pressure water (Watson & O'Loughlin 1990) or compressed air (Marden et al. 2005) to remove soil surrounding the roots. The whole root system is often extracted from the soil for smaller trees, though roots less than about 0.5–1.0 mm are not possible to remove intact. An alternative to whole tree root system extraction is the trench profile wall method, in which trenches are dug at different radial distances from the stem (Giadrossich et al. 2017). Trenches may be continuous/annular (e.g., Giadrossich et al. 2017) or of a fixed dimension (Ross et al. 2004, Douglas et al. 2010). Trenches are generally used to measure root distribution and are not suitable for whole tree biomass or root length assessment. There have also been trials with planted species in rhizotrons, which are essentially containers, either above or below ground, with one side usually consisting of clear Perspex to enable developing roots to be observed (Thomas et al. 1996). These are common for studying fine root dynamics.

Once exposed, the root system is usually drawn or photographed (e.g., Cameron 1963) before measurements are made of below-ground tree components. Usually, some above-ground measurements are taken as well, particularly tree height, diameter at breast height (DBH), canopy spread, root collar-diameter (RCD—sometimes referred to as ground line diameter or basal stem diameter), which are used for determining allometric relationships. At the very least, maximum root depth and maximum lateral root spread are recorded, but other information, such as root branching (using a hierarchical typology), root taper, colour, morphological root form, may also be recorded. Excavated root systems are usually recorded with reference to a horizontal or vertical grid (e.g., Douglas et al. 2010), or they may be partitioned into annular segments (e.g., Somerville 1979; Czernin & Phillips 2005; Marden et al. 2005) (Fig. 2). However, unlike overseas studies, 3D architecture analysis and modelling (e.g., Gartner & Denier 2006; Danjon & Reubens 2008) has not been applied in New Zealand studies. In some studies, roots are assigned to cardinal/radial segments (e.g., Czernin & Phillips 2005; Giadrossich et al. 2017), but in others they are bulked within the whole radial annulus relative to the stem (i.e., 0–0.5 m, 0.5–1.0 m and so on – Fig. 2). To obtain root distribution information at the appropriate depth or distance from the stem, the diameters of individual roots are measured with callipers at the appropriate class boundary, usually to 0.1 to 1 mm accuracy. For each annular segment, root length and below-ground biomass are then determined by washing roots clean of soil and cutting and grouping according to diameter (size–classes: < 1 mm (fibrous), 1–2 mm, 2–5 mm, 5–10 mm, 10–20 mm, 20–50 mm, 50–100 mm (and even larger classes where necessary), root bole or stump) (Böhm 1979). DBH, RCD and root measurements are usually made over–bark. Total root length in each diameter size–class is measured before they are oven-dried by placing root segments end to end against a measuring tape. The oven-dry weight (i.e., after drying at 100 degrees C) of roots is usually recorded to the nearest 0.1 g in studies where biomass is assessed.

One of the drawbacks of tree root excavations (particularly whole tree root systems) is that it is time-consuming and costly, especially for larger trees. Even the root systems of smaller trees a few metres high can take a team of two people 1–2 days to extract depending on the method, and larger trees can take a week to excavate with four people. Therefore, time and cost limitations have tended to limit both the number of trees assessed for any one species or their age since planting, with the result that detailed data on old or large trees are rare. A further consequence is that studies tend to be limited in their statistical robustness (low sample number (N)), meaning that allometric relationships or regression models (discussed later) have limited explanatory power. For these reasons, there are only a few studies that have reported results with larger numbers of root systems on bigger trees producing interesting and statistically reliable results (e.g., Danjon et al. 2005). Nevertheless, even though root information may be limited to only a few sample trees in many studies, such studies have been essential for improving our understanding, and for developing and validating models of root structure and function.

Regarding root morphology and how it links to soil reinforcement, the definition of “structural” or “coarse” roots has changed over time, as has the perceived importance of coarse versus fine roots as they relate to soil reinforcement and slope stability. Measures of total structural root length (e.g., Smit et al. 2000; Watson & Tombleson 2002), a proxy indicator for comparing trees in terms of soil reinforcement, can thus vary between

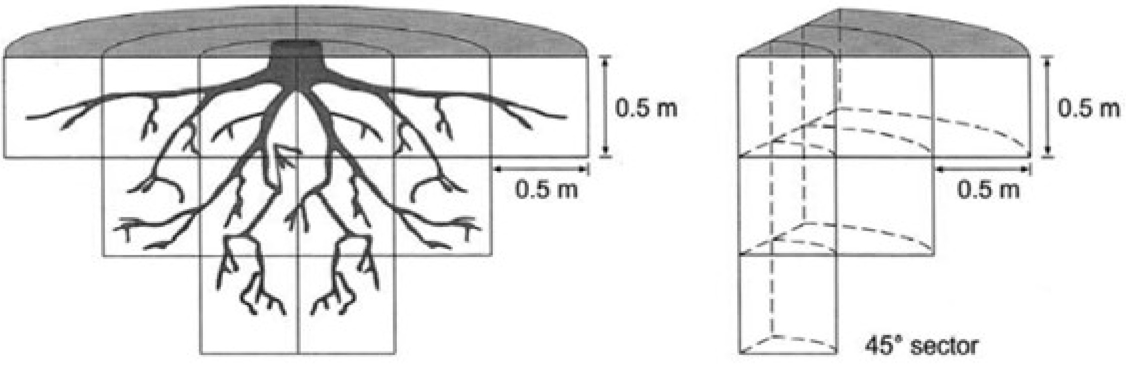

FIGURE 2: Root system partitioning following Watson & Tombleson (2002) and Czernin & Phillips (2005).

studies depending on where the lowest diameter cut off is (i.e., > 1 mm, > 2 mm or occasionally > 5 mm). Some early New Zealand studies defined structural roots (or coarse roots) as being > 2 mm (e.g., Watson & O'Loughlin 1990). Mickovski (2001) defined structural roots as those lateral roots having a diameter > 20 mm at a distance of 200 mm from the tree trunk. However, the term "structural roots" appears less frequently now in the literature. The diameter cut-off issue also applies to interspecies comparisons of root biomass (Phillips and Watson 1994; Phillips et al. 2013).

Based on a study of 22-year-old radiata pine (see Table 1 for species names and descriptions) root systems in New Zealand, Giadrossich et al. (2020) suggested a minimum number of trenches and trees required to obtain the characteristic value of lateral root reinforcement for a tree within acceptable limits. In this study, they found that 4.5 root systems where roots are exposed in trenches encircling 360 degrees around a tree and cumulative trench lengths of 28 and 56 m for 1 and 2 m distance from the tree, respectively, were appropriate to characterise the lateral root reinforcement for this species.

Root properties – tensile strength

Root properties such as root tensile strength, root elasticity, root pull-out resistance and shear strength of root reinforced soil are assessed using several methods (Giadrossich et al. 2017). Root tensile strength is usually determined in the laboratory using a pulling device that loads the root (usually a "straight" section 40–200 mm in length) until it breaks (O'Loughlin & Watson 1979). One of the issues with such tests is how the root is clamped at each end to avoid slippage of the root from the clamp and minimise damage to the root. Determining the validity of a tensile test has also been a matter of debate (e.g., Hales et al. 2013) as the root may break at or near the clamp or rupture near one end of the root, particularly if the root tapers. Some researchers only kept results when the root broke in the middle (e.g., Bischetti et al. 2005) though this could bias upwards the strength of roots. Root diameters up to about 20 mm can be tested this way (Giadrossich et al. 2017).

A field pull-out test consists of pulling a root out of the soil from a trench towards the stem using a device that usually consists of a metal frame and a winch. Roots of up to 60 mm have been successfully tested. Similar clamping issues exist to those in laboratory tests, and various solutions have been tried. A load cell records the force applied, and a sensor records the displacement (see Fig. 3 of Giadrossich et al. 2017). Root failure is a combination of multiple and sequential breakages depending on the size and number of branches. Field pull-out tests highlight the large natural variability of mechanical properties of roots and are used to estimate root reinforcement in some root models (e.g., root bundle model – Schwarz et al. 2013). Lastly, direct shear tests of soil containing roots are also used to estimate root reinforcement or obtain the necessary model input parameters. These tests can be conducted in the laboratory or the field, and shear boxes range in size from 60 mm up to 1000 mm (see Giadrossich et al. 2017 for more details). Different tests can be conducted – strain-loading or stress-loading, though stress-controlled tests are probably closer to a real field situation. Several New Zealand studies used field direct shear boxes to test root reinforced soils (e.g., O'Loughlin et al. 1982; Ekanayake et al. 1997; Ekanayake & Phillips 2002) or have used hydraulic rams to shear test whole trees (Wu & Watson 1998).

Tree stability and wind firmness

Various winching methods have been used in New Zealand studies to simulate wind stress on trees, to pull out whole trees, or to measure wind-induced forces in roots in wind-related studies (Somerville 1979; Watson 1995; Papesch et al. 1997; Moore 2000; Watson 2000; Moore & Gardiner 2001). Essentially, trees are pulled over with a winch, cable and pulley system, and the cable tension required to cause tree failure (defined as the point when the maximum applied load is reached) is measured using a load cell. The nominal height of the cable attachment is usually 30–50% of the tree height (Moore 2000). Root plate dimensions are usually recorded – diameter and depth. In some cases, tree stability has been reported where trials using controls against cultivation treatments such as v-blading, mounding, ripping or bedding (e.g., Hunter & Skinner 1986).

Modelling related to root information

Roots are components of a biological system, and as such allometric relationships are commonly used to illustrate how characteristics or traits of plants change as they grow. For many New Zealand studies, linear regression or exponential growth analysis is usually used to develop allometric relationships between tree DBH or RCD and information obtained from empirical measurements of total root length, maximum root spread, below-ground biomass, canopy spread, and tree height (e.g., Marden et al. 2020). These relationships (or their results) are then used as inputs for other models that focus on quantifying slope stability (Ekanayake & Phillips 1999, Schwarz et al. 2016) and soil reinforcement (Giadrossich et al. 2017) for below-ground biomass estimation (e.g., Marden et al. 2016) and carbon sequestration (Hollinger et al. 1993) or carbon turnover assessments (Thomas et al. 1996).

Root site occupancy is a term that has been used to describe how trees interact within a stand, and ultimately how they contribute to soil reinforcement to reduce erosion. Initially defined by Watson et al. (1999), it was later modified by Phillips et al.[vi] to lateral root site occupancy. Full lateral root site occupancy occurs when lateral roots of adjacent trees begin to overlap. A plan view of the tree root system is projected onto the ground as a circle, and, as the tree grows, the circle representing the extent of lateral roots increases in size until it touches the circle of the adjacent tree. At this point, 100% lateral root site occupancy is achieved. Lateral root site occupancy has been used to compare the effectiveness of different plant species (Phillips et al.[vi]). However, it is acknowledged that in most situations, roots of trees

TABLE 1: New Zealand studies where tree roots have been examined to assist understanding of soil reinforcement and tree wind firmness, and where data are presented. Does not include details of studies on plant seedlings nor specific numbers of laboratory root tensile tests.

Species common name	**Latin name**	**Age (time since planting) (years)**	**Number of plants assessed or excavated**	**Study type**	**Root study focus**	**Reference/researcher/*endnote***
Mānuka	*Leptospermum scoparium*	Not given < 50	9	Field, natural stand	Root architecture, distribution, biomass, root strength	Watson & O'Loughlin (1985)
		1–5	30	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Watson & Marden (2004); Marden et al. (2005); Marden et al. (2018b)
		3–6	22	Planted trial	Root architecture, distribution, biomass, modelling	Marden & Lambie (2016); Marden et al. (2020); *iii*
Kānuka	*Kunzia ericoides*	Not given < 50	1	Field, natural stand	Root architecture, distribution, biomass, root strength	Watson & O'Loughlin (1985)
		6, 16, 32	15	Field, natural stand, laboratory testing	Root architecture, distribution, biomass, root strength	Watson et al. (1995); Watson et al. (1997)
		16–40	11	Field testing	Shear testing, modelling	Ekanayake et al. 1997, 2004
Cabbage tree	*Cordyline australis*	1–25	13	Field, natural stand, field and laboratory testing	Root architecture, distribution, biomass, root strength	Czernin (2002); Czernin & Phillips (2005)
		1–5	50	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Marden et al. (2005, 2018b); Watson & Marden (2004); Watson et al. (2007)
Lemonwood	*Pittosporum eugenoides*	1–5	50	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Marden et al. (2005); Watson & Marden (2004)
Ribbonwood	*Plagianthus regius*	1–5	50	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Marden et al. (2005); Watson & Marden (2004)
Rewarewa	*Knightia excelsa*	1–5	49	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Marden et al. (2005); Watson & Marden (2004)
Kowhai	*Sophora tetraptera*	1–5	44	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Marden et al. (2005); Watson & Marden (2004)
Lacebark	*Hoheria sexstylosa*	1–5	48	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Marden et al. (2005); Watson & Marden (2004)
Māpou	*Myrsine australis*	1–5	50	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Marden et al. (2005); Watson & Marden (2004)
Kōhūhū	*Pittosporum tenuifolium*	1–5	49	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Marden et al. (2005); Watson & Marden (2004)
Tutu	*Coriaria arborea*	1–5	43	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Marden et al. (2005); Watson & Marden (2004)
Karamū	*Coprosma robusta*	1–5	45	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Marden et al. (2005); Watson & Marden (2004)
Fivefinger	*Pseudopanax arboreus*	1–5	46	Planted trial, laboratory testing	Root architecture, distribution, biomass, root strength	Marden et al. (2005); Watson & Marden (2004)

TABLE 1: *continued*

Species common name	**Latin name**	**Age (time since planting) (years)**	**Number of plants assessed or excavated**	**Study type**	**Root study focus**	**Reference/researcher/***endnote*
Southern Rata	*Metrosideros umbellata*	Not given	?	Field, natural stand, laboratory testing	Root architecture, root strength	Watson & O'Loughlin 1985
Kamahi	*Weinmannia racemosa*			Field, natural stand, laboratory testing	Root strength	Phillips & Watson 1994; *ix*
Hard Beech	*Nothofagus truncata*	15–320	7	Field, natural stand, laboratory testing	Biomass	Phillips & Watson 1994; *ii*
Mountain beech	*Nothofagus solandri var. cliffortioides*	52	9–18	Field, natural stand, laboratory testing	Biomass	Benecke & Nordmeyer (1982)
Titoki	*Alectryon excelsus*	1–5	49	Planted trial	Root architecture, biomass, allometry	Marden et al. (2018a)
Matai	*Prumnopitys taxifolia*	1–5	50	Planted trial	Root architecture, biomass, allometry	Marden et al. (2018a)
Kauri	*Agathis australis*	1–5	50	Planted trial	Root architecture, biomass, allometry	Marden et al. (2018a)
Miro	*Prumnopitys ferruginea*	1–5	50	Planted trial	Root architecture, biomass, allometry	Marden et al. (2018a)
Totara	*Podocarpus totara*	1–5	50	Planted trial	Root architecture, biomass, allometry	Marden et al. (2018a)
Kahikatea	*Dacrycarpus dacrydioides*	1–5	50	Planted trial	Root architecture, biomass, allometry	Marden et al. (2018a)
Puriri	*Vitex lucens*	1–5	41	Planted trial	Root architecture, biomass, allometry	Marden et al. (2018a)
Rimu	*Dacrydium cupressinum*	1–5	50	Planted trial	Root architecture, biomass, allometry	Marden et al. (2018a)
		2–50	13	Planted trial	Root architecture	Cameron (1963)
Tawa	*Beilschmiedia tawa*	2–50	13	Planted trial	Root architecture	Cameron (1963)
Radiata pine	*Pinus radiata*	18	8	Planted stand	Root architecture, biomass	Will (1966)
		11.5	61	Planted stand	Root architecture, wind firmness	Somerville (1979)
		3–8	97	Planted trial	Biomass, allometry	Jackson & Chittenden (1981)
		5	18	Planted trial	Biomass	Clinton (1991)
		8, 16, 25	13	Planted stand	Root architecture, distribution, biomass	Watson & O'Loughlin (1990); Watson et al. (1995)

TABLE 1: *continued*

Species common name	**Latin name**	**Age (time since planting) (years)**	**Number of plants assessed or excavated**	**Study type**	**Root study focus**	**Reference/researcher/***endnote*
Radiata pine	*Pinus radiata*		6	Planted stand	Biomass	Phillips & Watson (1994); *ii*
			3	Planted stand	Whole tree pull–out	Phillips & Watson (1994)
		2	12	Planted stand	Shear testing, modelling	Ekanayake et al. 1997, 2004;
		6–8	3	Planted stand	Whole tree shear test	Wu & Watson (1998)
		0–3	16	Planted trial	Root architecture, distribution, biomass	Phillips et al. (2015)
		1–4	134	Planted trial	Root architecture, biomass, allometry	Marden et al. (2016)
		22		Planted stand	Root pull–out, root distribution	Giadrossich et al. (2020); Hiltebrand et al. (2016)
		3	26–32	Planted trial	Root architecture, wind firmness	Fawkner (2001)
				Planted trial	Root architecture, wind firmness,	Gautam et al. (1999)
		2–3	98	Planted stands	Root architecture, wind firmness	Mason (1985)
		8	30	Planted trial	Root architecture, wind firmness,	Balneaves & de la Mare (1989)
		9-30	164	Planted stands	Wind firmness	Moore (2000)
		7-9	?	Planted stands	Wind firmness	Wendelken (1955)
Eucalypt sp.	*Eucalyptus botryoides*	3	16		Root architecture	Unpublished FRI data; Watson & O'Loughlin
	Eucalyptus fastigata	0–3	16		Root architecture, distribution, biomass	Phillips et al. (2015)
Lodgepole pine	*Pinus contorta*	2–23	27		Root architecture	Benecke & Nordmeyer 1982; *v*
Mountain pine	*Pinus mugo*	13–20	13		Root architecture, biomass	*ii*; *ix*
Douglas-fir	*Pseudotsuga menziesii*	15	1		Root architecture, root strength	*iv*
		0–3	11		Root architecture, distribution, biomass	Phillips et al. (2015)
		17–35	20		Wind firmness	Moore & Gardiner (2001)

TABLE 1: *continued*

Species common name	Latin name	Age (time since planting) (years)	Number of plants assessed or excavated	Study type	Root study focus	Reference/researcher/*endnote*
Redwood	*Sequoia sempervirens*	0–3	15		Root architecture, distribution, biomass	Phillips et al. (2015)
		1–4	15		Root architecture, distribution, biomass	Phillips et al. (2013)
Cupressus	*Cupressus lusitanica*	0–3	15		Root architecture, distribution, biomass	Phillips et al. (2015)
Alder	*Alnus rubra*	0–3	14		Root architecture, distribution, biomass	Phillips et al. (2015)
Cherry	*Prunus serrulatus*	0–3	15		Root architecture, distribution, biomass	Phillips et al. (2015)
Oak	*Quercus robur*	0–3	15		Root architecture, distribution, biomass	Phillips et al. (2015)
Tasmanian blackwood	*Acacia melanoxylon*	0–3	16		Root architecture, distribution, biomass	Phillips et al. (2015)
Poplar sp.	*Populus x euramericana* (Dode) Guinier cv. 'I–78'; *P. x euramericana* (Dode) Guinier cv. 'I–488'; *P. yunnanensis* (Dode); *P. deltoides* Marsh cv. 'A60/129'	–	1	Planted trial	Root architecture; distribution; root strength	Hathaway 1973; Hathaway & Penny (1975)
	P. maximowiczii; *P. deltoides* angulate cv 'Carolinensis'; *P. x euramericana* cv 'Flevo', 'I 214' and I178; *P. x canescens*	3, 5, 6	8	Planted	Root architecture, root distribution	*viii*
	Veronese poplar (*Populus deltoides x nigra*)	0.4–0.6	6	Planted trial	Root length, biomass	Sulaiman et al. (2005); Sulaiman (2006)
	Populus x euramericana, 'Veronese poplar'	–	–	Planted	Root strength	*xi*

TABLE 1: *continued*

Species common name	**Latin name**	**Age (time since planting) (years)**	**Number of plants assessed or excavated**	**Study type**	**Root study focus**	**Reference/researcher/***endnote*
Poplar sp.	*Populus deltoides x nigra* 'Veronese'	5, 7, 9.5	3	Planted	Root architecture, biomass, distribution	McIvor et al. (2008);
	Populus deltoides x nigra 'Veronese'	11.5	3	Planted	Root architecture, biomass, root length, allometry	McIvor et al. (2009); *i*
	Populus deltoides Marshall x *P. nigra* L. clone 'Tasman'	9–11	6	Planted	Root distribution, biomass	Douglas et al. (2010)
	Populus deltoides Marshall × *nigra* L. and other poplar clones	1	5	Planted trial	Root distribution, planting type	Douglas et al. (2016)
	Populus sp clones (10)	0.2	10	Greenhouse trial	Root length, root biomass	McIvor et al. (2014)
	Populus deltoides × yunnanensis 'Kawa'; *Populus deltoides × P. nigra* 'Veronese'	0.75	6	Planted trial	Root architecture, distribution, biomass, planting type	Phillips et al. (2014)
	–	–	–	–	Modelling, root distribution	Schwarz et al. (2016)
	Populus deltoides × nigra	1–3	3	Planted trial	Biomass, root distribution	McIvor et al. (2020)
Willow sp.	*Salix matsudana* Koidz.; *Salix purpurea* L. cv. 'Booth'	–	1	Planted trial	Root strength	Hathaway (1973); Hathaway & Penny (1975)
	Salix sp.	3–6	–	Planted	Pull-out, root strength, root morphology	Oplatka & Sutherland (1995)
	Salix matsudana x Alba 'Tangoio'	0.4–0.6	6	Planted trial	Root length, biomass	Sulaiman et al. (2005); Sulaiman (2006)
	Salix matsudana × alba 'Hiwinui'; *Salix matsudana × alba* 'Tangoio'	0.75	6	Planted trial	Root architecture, distribution, biomass, planting type	Phillips et al. (2014)
	Salix sp clones (11)	0.2	11	Greenhouse trial	Root length, root biomass	McIvor et al. (2014)

FIGURE 3: 25-year-old *Pinus radiata* from Mangatu Forest. One of Watson & O'Loughlin's (1990) study trees. Photo J. Barran.

are often not symmetrical around the stem and that individual 'long' roots may over-represent the "true" value of lateral root site occupancy and, by implication, soil reinforcement. To overcome this, Phillips et al. (2011) extended this concept and developed an improved method to estimate the 'effective root spread'. Instead of using the mean maximum root spread they defined a parameter called the Root Reinforcement Index using the root surface area and planar soil area occupied roots. The method was used to compare root site occupancy of young New Zealand native plants.

Root information is used in different ways in soil reinforcement and slope stability models, which are many and varied in their data requirements and input parameters. However, in general terms, data derived from root diameters, root length, root biomass, root spread, root depth, DBH and/or RCD, and root tensile strength or pull-out resistance are generally minimum requirements. Slope stability and root reinforcement models have become more sophisticated in recent years as access to improved computing power has developed. However, they all rely on broad geo-mechanical and hydrological underpinnings and generally limited field and experimental data. In a similar way, mechanistic models are generally used to assess the relative wind firmness of trees or to assess wind risk (e.g., Gardiner & Quine 2000). Such models predict the minimum windspeed required to generate an overturning moment equal to the maximum resistive bending moment that the trees can provide. The latter term is calculated using empirical relationships fitted to data collected from tree winching studies.

Root morphology and architecture including root distribution

Overview

Root morphology is both genetically controlled and modified by environmental or edaphic factors. The development of a particular root morphology largely dictates the long–term growth of the tree as well as its contribution to soil reinforcement and slope stability. For example, the direction in which a root grows is a key parameter for soil exploration and the response to environmental cues. The directional characteristics of growth are termed tropisms and, depending on whether plants grow towards a signal or away from it, the tropism is defined as positive or negative, respectively. There are multiple tropisms, including gravitropism (gravity), phototropism (light), hydrotropism (water) and thigmotropism (touch) (Esmon et al. 2005). While roots adapt and adjust their growth to changing environments, the adjustment is possible through mechanisms that modulate a diverse set of root traits (growth rate, diameter, growth direction and lateral root formation) which occurs at the cellular level (Slovak et al. 2016). Here a multitude of genes and gene networks precisely regulate development in space and tune it to environmental conditions. Root growth regulation is a highly complicated process and is controlled at many different levels by complex actions of gene networks in both time and space. How these contribute to the traits that shape the root system architecture is of biological interest and is also key to breeding and engineering better-performing plants. As far as the authors are aware, the role of genetics (other than through 'traditional' breeding efforts, e.g., the growth and form (GF) breed (Kimberley et al. 2016)) in determining a tree's root morphology and architecture, particularly beyond the seedling stage, has not yet been researched in New Zealand. However, Marden et al. (2016) determined there were no differences in root morphology, architecture or growth rate of radiata pine between plant material types (seedlings vs cuttings) with different genetics within the 5–year period covered by their experiment. They concluded that environmental factors (e.g., slope, aspect, soil depth, hardness of underlying bedrock, pathways of least resistance (cracks, fissures, concentration of roots in buried soil horizons, the search for moisture, oxygen and nutrients, and wind direction) played a greater role than genetics in root morphology and architecture.

Beyond the embryonic stages, a tree's roots, at least in a root system architecture sense, are defined in several ways. Taproot is used to describe the main vertical root directly below the bole/stem of the tree, oblique roots also arise from under the root bole but grow diagonally (not vertical or lateral but intermediate between these), lateral roots are roots coming from the central bole but in the horizontal plane, and sinker root refers to vertical roots arising from laterals (Phillips & Watson 1994). Tree root form or architecture can be considered in terms of the simplified three-dimensional shape of the root system. Depth and lateral spread are the gross elements of form (Sutton 1969). Three general forms exist — taproot, heartroot, and plateroot (Wilde 1958) though a fourth form "secondary sinker root systems" has also been described (Kostler et al. 1968). All the New Zealand studies refer to the three general forms.

Studies of root system morphology in New Zealand include both indigenous and exotic forestry species. Although the total number of trees studied for each species is relatively small, particularly across a range of ages (or tree sizes), most common timber species and many of those used in ecological restoration projects have been covered (Table 1). Radiata pine, kānuka, mānuka and poplar have had the most research effort and number of studies. Like sample size, the range of different growing environments (soils, climate, geology) in which studies of tree roots of the same species have been done is limited even though these physical environmental factors are key in determining the nature and extent of a tree's root system (Phillips & Watson 1994) as is the physical treatment of soils where factors limit root growth (Ross et al. 2004). While similarities in morphology exist within a particular species, the overall shape and extent of both lateral and vertical roots are largely governed by physical site conditions. Lateral root development generally follows the development of the tree crown and usually exceeds it, and depending on stem spacing, intertwining and competition between neighbouring trees are common. Some species form grafts between roots of the same tree or between neighbouring trees of the same species (e.g., radiata pine, Will 1966).

New Zealand studies have ranged from descriptive, including photographing or drawing of root systems (e.g., Watson & O'Loughlin 1985, Ross et al. 2004, [vii]), to the development of more systematic assessments and indices (e.g., Somerville 1979; Balneaves & de la Mare 1989). Reported New Zealand root morphology indices (Balneaves & de la Mare 1989; Mason 1985) are generally subjective and have been used to compare tree performance following different plant establishment treatments such as soil ripping. They tend to focus on an appraisal of taproot distortion, lateral root arrangement, and root tangle. Such systems are still used to assess nursery seedlings and in situations where trees may have toppled due to wind. Brown et al. (1996) developed an index for describing the radial "evenness" of lateral tree roots with unevenness defined as the deviation from a perfectly uniform root distribution. This approach, however, has not been followed in subsequent studies.

Many studies have reported root architecture asymmetry with the greatest lateral root development on steeper slopes often occurring in the upslope direction (e.g., di Iorio et al. 2005; Khuder et al. 2007; Marden et al. 2018a). Such asymmetric architecture has been called "bilateral–fan shape" (Chiatante et al. 2003). This "bilateral–fan shape" was observed by Marden et al. (2016) on juvenile radiata pine growing on steep slopes near Gisborne. In some cases, there are also large areas of the soil that are devoid of roots. Poplar root systems exhibit this behaviour particularly well. This absence of tree roots is more common in planted wider spaced stands than in natural high–density plantation or natural forest situations but can also occur in response to extreme cultivation.

Exotic trees

New Zealand studies of exotic tree root systems prior to the 1960s were few (at least in the published New Zealand literature). Primarily, but not exclusively, attention has been on New Zealand's main exotic plantation species — radiata pine. Other exotic species have had limited attention (see Phillips & Watson 1994). Poplars and willows are the next most studied species.

Radiata pine

One of the earliest studies of radiata pine roots contained photographs of close-growing pine trees with the surface soils removed, showing lateral roots, though the whole tree was not excavated (Wendleken 1955). This study focussed on wind firmness, and it established that on the Canterbury Plains, where there is often a compacted subsoil, deep penetration by vertical roots is effectively prevented, which contributes to the tree's proneness to wind toppling (see later section). Will (1966) showed several photographs of almost fully exposed 18-year-old root systems growing in pumice soils. These are the earliest photographs of fully exposed tree root systems in New Zealand we could find apart from the partially exposed roots systems of tawa and rimu in Cameron's (1963) study. One of the key features noted by Will (1966) were common root grafts between living and harvested radiata pine trees which were sufficient to keep the felled tree stumps alive.

Nursery–grown radiata pine seedlings generally possess fibrous root systems without dominant taproots as these are removed in the nursery beds (trimmed to a length of 100 mm measured from the root collar). Several studies (e.g., Watson & Tombleson 2002, 2004; Marden et al. 2016) have assessed the root systems and root metrics of various seedling types in the early years of growth (seedlings and cuttings with different levels of genetic improvement (as defined by their growth and form (GF) factor— Maclaren 1993)). Results vary between studies, with some showing no significant differences in key root metrics while others showed differences. After planting, pine root systems grow rapidly, with growth concentrated towards developing a shallow system of strong lateral roots that radiate outwards from the central root bole. Within 5–7 years after planting, the bole and major laterals give rise to vertical sinker roots which, in deep soils, may descend several metres (O'Loughlin & Zhang 1986). However, vertical root development is often limited to less than 2.0 m by stony subsoils, bedrock/welded pumice floes, pans or high water tables. Several studies of radiata pine roots in plantations of different ages up to 25 years have largely illuminated the general morphology and development of pine root systems (Somerville 1979; Will 1966; O'Loughlin 1984, 1985; Watson & O'Loughlin 1990).

Watson & O'Loughlin (1990), in their Mangatu Forest study, found lateral roots had a maximum length of 4.7, 6.4, and 10.4 m at ages 8, 16, and 25 years, respectively, while vertical roots grew to depths of 2.1, 2.6, and 3.1 m respectively. At 8 years old, the lateral roots were confined mainly to the upper 40 cm of soil, and vertical roots all originated directly below the stump. By 25 years, the root networks had developed into massive systems dominated by shallow lateral roots that would have overlapped and intertwined at normal plantation stand densities. There was strong root development across and down the slope and the maximum lateral root extension observed was 10.4 m. Of note was that vertical roots originating from the underside of the main laterals within 2.5 m of the stump had grown to a size and depth similar to those growing from under the stump (Fig. 3). Furthermore, while the larger vertical roots had penetrated to a maximum depth of 3.1 m, the average depth was about 2.6 m. A saturated clay layer restricted growth, and at this depth, coarse 70 mm roots branched into many smaller gnarled roots once they penetrated the clay. They concluded that an increase in stoniness with soil depth, poor drainage or fluctuating ground–water table, and poor growing media, i.e., damp deoxygenated clays, were the dominant factors influencing vertical root development in older trees at this site.

Where root-impeding subsoils or pans are present, cultivation that breaks up such layers has a marked effect on root growth, typically increasing the density and depth of rooting in the remediated zone (Ross et al. 2004). Ross et al.[vii] showed that cultivation by one-way ripping resulted in a U-shaped zone of loosened subsoil down to 65–70 cm depth (cross-sectional area of about 1800 cm^2), still evident after 31 years. The ripping zone of subsoil had significantly lower soil strengths (penetration resistances) and bulk densities. Significantly greater root development occurred into these loosened subsoils, particularly medium and large roots.

To address a need for information on juvenile radiata pine to support planting density guidelines in erosion-prone regions, Marden et al. (2016) trialled five seed lots (seedlings and cuttings with different genetic (GF) ratings) in a randomised block design. The trial assessed above and below-ground components over 4 years. There were no consistently significant differences among seed lots in terms of lateral root spread or maximum root depth until year 4, when two of the five outperformed the others. However, there was no difference in the root/shoot biomass ratios between seed lots in any year of the trial, remaining relatively constant at 0.22.

Poplar

Poplar species, most of which in New Zealand are grown from planted poles, exhibit strong lateral root growth (e.g., McIvor et al. 2005) but do not generally produce the same number of sinker roots as radiata pine, especially when grown in 'natural' field conditions. Lateral poplar roots can grow rapidly and extend considerable distances from the stem (> 14 m in a 7-year-old tree (McIvor et al. 2005), 8.4 m after 9 months (Phillips et al. 2014)). These long smooth-barked laterals are rope-like and tend to be ovoid in cross-section with some branching (Fig. 4). Generally, roots are spatially

FIGURE 4: Poplar 'Kawa' root development 3 years after establishment from a pole grown in a trial near Gisborne (Phillips et al. 2014) (Photo: C. Phillips)

symmetrical about the stem (e.g., Phillips et al. 2014) but may be asymmetric if growing on a slope (McIvor et al. 2009). The authors concluded that unevenness of the coarse root distribution, particularly in upper slope trees, can be explained by limitations in soil moisture during the growing season as much as by resistance to stress from slope and wind. The same study found that the distribution of coarse roots largely occurs within the top 40 cm of the soil profile, as observed in other studies of root distribution in *Populus* and other tree species (e.g., Watson & O'Loughlin 1990).

Redwood

Redwood has been suggested as a suitable tree species for erosion-prone hill country in New Zealand (Burdon 1975) because of its ability to coppice once the stem is removed, i.e., the roots remain alive, which means that a large degree of root reinforcement of the soil is not lost when the trees are harvested. Phillips et al. (2013) assessed root development in redwood trees up to 4 years old at two sites (one in South Island on Hurunui Steepland soils and one in North Island on Taihape Steepland soils). They found that roots were distributed symmetrically around the root stump, and they were numerous and fine. Roots < 5 mm made up most of the total root length, and roots < 10 mm comprised 98% of total root length in 4-year-old trees. The coarsest roots were close to the stump and reached 42 mm in diameter. The study concluded that when compared to radiata pine, redwoods offer an alternative as a species for erosion control.

Indigenous trees

There are few early studies of the roots of New Zealand's indigenous trees (e.g., Cockayne 1921; Allan 1926). They tended to focus on surface roots and comment on the lateral extent of the root systems relative to the stem or crown. Hinds & Reid (1956) made the first attempt to classify the main timber species' root systems and describe their typical forms that showed variation between the species described. A key result of this work was the observation that a species' root system varied in form from soil type to soil type, and even within the same soil type, there was a high degree of variation in rooting habit. It was not until Cameron's (1963) studies of rimu and tawa that root systems of larger trees other than seedlings (mature trees, windthrown trees, poles, saplings) were examined following excavation or trenching. More modern studies of root systems in natural forests/stands include mānuka (Watson & O'Loughlin 1985; Marden & Phillips 2015; Marden et al. 2020), cabbage tree (Czernin & Phillips 2005), and kānuka (Watson et al. 1995; Ekanayake et al. 1997). The remaining studies have been of planted trials (e.g., Marden et al. 2005, 2007, 2018a, b) or rehabilitation plantings, such as at mine sites (Watson et al.[x]) and riparian margins. In the mine site study, eleven 7-year-old trees (mānuka/kānuka, kōhūhū, cabbage tree) were excavated, photographed, measured and described and biomass assessments with depth made.

Trials involving planted indigenous species specifically to look at root system development (as well as biomass) to enhance soil reinforcement began in the early 2000s. Twelve indigenous woody species commonly found growing naturally in unstable riparian slope and/or bank environments were assessed during the first 5 years following establishment (Marden et al. 2005). Three non-woody species (sedge grass, toe toe, and mountain flax) were also included in the first two years of this trial. In a similar trial at the same site, eight common indigenous conifer and broadleaved forest species were assessed during the first five years of establishment (Marden et al. 2018a). Marden et al. (2020) assessed root systems of 3-, 4- and 6-year-old plantation mānuka established on different hill country landforms at Lake Tutira. Nine trees of each younger age class and four of the older age class were hand excavated.

In general terms, most of the indigenous tree species in New Zealand tend to have shallow plate-like or heart-shaped root systems, generally consisting of surface laterals and fine roots, but they can vary widely both within and between species. Furthermore, the root morphology is highly dependent on edaphic factors (soil/rock type and structure (soil strength and pore sizes and soil aeration), pH, temperature, soil moisture, organic C and N (particularly nitrate) content) and soil biological activity including distribution of old root channels) and climate. Root morphology may also be influenced by mycorrhizal status – beech seedlings in soils near *Nothofagus* had 3.4 times greater biomass than those in soils distant from trees (Dickie et al. 2012). Generally, the root plate extends well beyond the radius of the crown (Cameron 1963). Sinkers arise from lateral roots, and a tap root may or may not be present. For example, rimu seedlings typically have a weak root system lacking either a tap root or a well–developed lateral root system (Cameron 1963, Norton et al. 1988). However, mānuka appears to be the exception with clearly well–developed tap and/or sinker roots arising from below the stump or from larger laterals close to the stump (Watson & O'Loughlin 1985; Watson et al.[x]; Marden et al. 2020). Fine feeding roots of indigenous species are largely confined to the humus and uppermost layers in both natural stands and planted situations. In studies where whole trees were excavated and/or more than a few individual trees assessed, the consensus is that lateral roots of indigenous plants are largely confined to the upper 0.5 m of soil, including most of the biomass and root length, and many of the long developed lateral roots tend to be found close to the surface (e.g., Watson et al. 1995).

Marden et al. (2005, 2018b) described root systems of mānuka and ten other indigenous species grown in a trial at year 5 as being heart-shaped. Only one trial species, cabbage tree, developed a tap-rooted system. Marden et al. (2020) suggested that the development of a heart-shaped root architecture may be an adaptation typical of early colonising species in their search for nutrients and surface water and to provide a higher level of near-surface soil reinforcement and tree stability (wind firmness) at a greater distance from the stem.

In a similar trial that observed root attributes of eight common indigenous evergreen conifer and broadleaved forest species during the first 5 years after establishment, a mixture of tap and plate root systems were observed (Marden et al. 2018a, b).

Published accounts on the architecture of mānuka root systems are largely descriptive. Mānuka may exhibit asymmetric root systems in plan view, with the bulk of the root development in the upslope direction (Watson & O'Loughlin 1985). In general, the root systems consist of a few main structural roots of small diameter, giving rise to a dense network of fine roots. The largest vertical roots originate directly under the tree stump, but others grow from the underside of the larger lateral roots within 0.5 m of the stump. Such sinker roots often taper rapidly and may penetrate beyond 0.5 m in depth, especially where the substrate allows it. Planted mānuka has been observed to reach depths of up to 1.0 m in 6-year-old plants (Watson et al.[x]; Marden et al. 2020). The mean maximum root spread (diameter of intact root system) of mānuka excavated 3 and 4 years after planting in Marden et al.'s (2020) study was not significantly different among landforms. However, the mean maximum root depth 6 years after planting on interfluves penetrated the deepest, reaching a maximum root depth of 1.0 m. On these sites with few physical limitations to root growth, their horizontal and vertical distribution was nonetheless highly asymmetric, leaving large areas of soil devoid of any roots. Like earlier studies, the bulk of the root biomass was confined to within 0.5 m of the ground surface.

Watson et al. (1995) described the root morphology of three age classes of mānuka. In young trees, the lateral roots were distributed asymmetrically around the stump, growing predominantly up and across the slope. By 32 years, the lateral root systems were well developed, with the larger roots at times intertwining with roots of adjacent trees. However, vertical roots of all age classes were poorly developed, with strongly-tapered taproots that often branched, though this may have been due to the presence of an increasing number of angular stones with depth. Sinker roots were growing to depths of 0.9 m at a radial distance of up to 1 m from the stump.

Indigenous trees and plants grow (or are perceived to grow) much slower than common exotics (Pollock 1986; Bergin & Gea 2007; Phillips et al. 2011). However, while the rate of development of both above and below-ground parts of New Zealand indigenous species may be slow relative to exotics, some species can grow quite quickly depending on the environments in which they are planted. For example, in Marden et al.'s (2020) study, data indicated root site occupancy of planted mānuka on "good" sites at even spacing of 3 × 3 m (1111 stems ha^{-1}) would occur 4–4.5 years after planting assuming mean root spread (diameter) (Marden et al. 2020). On poorer sites however, root site occupancy had not occurred after 6 years. At a less-dense rectangular spacing of 4 × 3 m (833 stems ha^{-1}), lateral root extension across the wider 4–m gap between planted rows would be further delayed until between 5 and 6 years after planting on the better sites but would not occur at all on slopes that were extensively-scarred by landslides. Radiata pine at comparable planting densities would reach root site occupancy in less than half the time for mānuka (Marden et al. 2016).

Root biomass and total root length

While early studies focused on understanding tree root architecture, root distribution and root strength to underpin erosion process studies in New Zealand, interest in gathering data on below-ground biomass was also high. This was because few studies had previously been conducted and root information was always hard-won, but also because there was increasing interest in understanding the allocation of carbon to below ground in the context of carbon sequestration as it pertained to climate change (e.g., Watt et al. 2012). Before the later detailed studies of root distribution and architecture, root biomass was also used as a proxy for root reinforcement, i.e., the greater mass of roots, the better the soil reinforcement. This paper does not intend to comprehensively review root biomass studies as this would require another paper of similar length, but it is briefly covered here since it is relevant to root reinforcement in soils, and as mentioned, root biomass was used as a proxy root reinforcement indicator to compare different species. Root biomass details for selected species are included in Table 2.

How a 'structural' root is defined (see earlier in Methods) also creates an issue when comparing root biomass information between studies. Root diameter cut-offs vary in measured estimates of "root biomass" (> 1 mm, > 2 mm, > 5 mm). Some studies include the root bole in below-ground biomass measurements, and others do not. Some report only parts of the whole system rather than from a fully excavated tree, and some only assess below-ground biomass from soil coring or trenching methods then endeavour to scale up to the whole tree or stand scale using allometric relationships. Root:shoot ratios and/or above- and below-ground biomass ratios may be presented in some studies rather than the actual data. Lastly, the actual method of assessing the oven-dry weights of roots may also vary (particularly the temperature). All these factors need to be considered when comparing measurement data or estimates between and within species obtained from different studies.

For more information on tree root biomass, the reader is directed to Easdale et al. (2019), which provides the most recent and comprehensive summary of root biomass allocation in natural southern temperate forests, though this includes studies other than from New Zealand. Papers by Watson et al. (1995), Beets et al. (2007), Marden et al. (2016, 2018a), Beets & Garrett (2018), and Paul et al. (2021) also contain useful information on New Zealand root biomass studies.

Root length

Total root length (i.e., the length of all root segments if laid end to end) has been used as an indicator for comparing species or plant types (seedlings, cuttings)

TABLE 2: Selected below–ground or oven dry mean root weight/biomass allometric relationships for various species from New Zealand studies (roots > 2 mm except where indicated). See Phillips & Watson (1994) and listed references for additional details.

Species common name	Allometric relationship where given	Information sources
Poplar	Root mass (kg) = 1.16 (dbh (cm)) – 7.56	McIvor et al. (2008)
	Log$_{10}$ root mass (kg) = 3.62 x log$_{10}$(dbh(cm)) – 3.52	McIvor et al. (2009)
Radiata pine	Root weight (kg) = 5.97 (dbh)$^{2.8068}$ x 10^{-3}	Jackson & Chittenden (1981)
	**Root weight (kg) = 6.25 (dbh)$^{2.7382}$ x 10^{-3}	
	Total root system weight (kg) = 5.87 (dbh)$^{2.938}$ x 10^{-3}	
	Total root weight = 13.7 (dbh) – 220	Watson & O'Loughlin (1990)
	*Total below–ground biomass (g) = 47.060e$^{0.037(\text{root collar diameter (mm)})}$	Marden et al. (2020)
Mānuka	Total root weight (kg) = 0.065 (tree basal area at breast height (cm^2)) – 0.613	Watson & O'Loughlin (1985)
	*Total root biomass (g) = 31.41exp$^{0.040(\text{root collar diameter(mm)})}$	Marden et al. (2020)
Kānuka	Total root weight (kg) = 7.69 X 10^{-6} (dbh)^3	Phillips & Watson (1994)
Rimu	Total root biomass (g) = 1.793 exp$^{(0.106\text{ root collar diameter (mm)})}$	Marden et al. (2018a)

**roots > 1 mm*
***roots > 5 mm*
dbh usually in cm
Oven dried weight usually in kg

for their ability to reinforce soils (Watson & Tombleson 2002) (Table 3). Essentially, the greater the total root length (above a nominal diameter, e.g., > 1, > 2, > 5 mm), the greater the interaction the plant has with the soil and the greater the soil reinforcement. This metric does not account for differences in root surface area between root segments of different diameters (i.e., taper), which would be a better indicator of the root-soil "bond" (e.g., Phillips et al. 2011). A few studies have examined root surface area and its relationship to soil reinforcement. Fawkner (2001) used root volume and root surface area to compare radiata pine planting treatments, and Phillips et al. (2011) used it in a model to compare root reinforcement and lateral root site occupancy of 11 indigenous species.

Like other root "metrics", a species' total root length can be affected by the environment in which the plant is growing. For example, McIvor et al. (2020) found total root length of trees grown in clay loam was greater than for trees grown in sandy loam, but those grown in pumice were considerably greater than for trees of the same age growing in these two soil types. Similarly, Marden et al. (2020) found variation in the total root length of planted mānuka trees grown on different landforms (interfluves, landslides and colluvial slopes). Further, for the largest mānuka root systems excavated in this study, only 5% of the total root length was located below 0.5 m depth. As the mānuka trees aged, the proportion of the total root length closest to the stem on the better interfluve sites declined more rapidly than on the other landforms, largely because on these sites, the roots found it easier to explore more resources such that by age 6 years, roots were out as far as 2.5–3.0 m from the root bole, though at this distance they represent only 0.2% of the total root length. Irrespective of landform type, 100% of the total length of roots > 1 mm of mānuka excavated 3 years after planting was confined to within 1.0 m of the root bole.

Mean total root lengths of young indigenous trees are generally less than equivalent-aged exotic trees (Marden et al. 2018b) (Table 3). For example, lemonwood after 5 years had a mean total root length > 1 mm of 197 m which was significantly different from the next best species, ribbonwood (160 m) and tutu (159 m). Marden et al. (2020) found plantation mānuka mean total root lengths (> 1 mm) of 13–161 m for 3–6-year-old trees grown on different landforms. 4-year-old redwood had mean total root length > 1 mm of 471 m (Phillips et al. 2013). Mean total root lengths > 1 mm in Phillips et al.'s (2015) study of 3-year-old exotics showed alder had the greatest total (1269 m) followed by cypress (837 m). Radiata pine had only 128 m (Fig. 5). Marden et al. (2016) examined the root development of juvenile radiata pine trees grown from five seed lots and found that by year 4, there was no consistently significant difference among seed lots in the distribution of total below-ground biomass or total below-ground root length (roots > 2 mm). They observed that for all seed lots combined, the root length of 95.5 m was more than double that reported for 3-year-old radiata pine (43 m) established at a trial on an alluvial terrace in Gisborne (Phillips et al. 2015) and that by year 4, the value was 204 m. In a Taranaki trial of bare-root cuttings, bare-root seedlings and direct-sown seedlings, the mean total root length > 2 mm of 3-year-old bare-root cuttings was significantly less than that for either direct-sown or bare-root seedlings ($p < 0.05$). Mean total root length for all three planting types was 60 m (range 35–75 m) (Watson & Tombleson 2002). In a similar trial near Tauranga mean total root length > 2 mm at 36 months was 15 m (range 13–17 m), and there were no statistically significant differences between bare-root seedlings and bare-root cuttings (Watson & Tombleson 2004).

In a 3-year field trial of different planting types of poplar and willow (wands, stakes, poles), Phillips

TABLE 3: Mean total root lengths (> 1 mm diameter) for a selection of species and ages since planting.

Species common name	Total root length > 1 mm (m)	Approx. age since planting (years)	Information sources
Mānuka	13–161	3–6	Marden et al. (2020)
Kauri	0.4–9.0	2–5	Marden et al. (2018a)
Puriri	2.9–112.4	2–5	Marden et al. (2018a)
Kahikatea	2.1–80.0	2–5	Marden et al. (2018a)
Lemonwood	197.4	5	Marden et al. (2018b)
Radiata pine	*144.1–801.8	8–25	Watson & O'Loughlin (1990)
	*10.1–204	1–4	Marden et al. (2016)
	16.0–128.1	1–3	Phillips et al. (2015)
Redwood	4.9–471.1	1–4	Phillips et al. (2013)
Poplar 'Veronese'	*79.4–663.5	5–9.5	McIvor et al. (2008)
	*287.9–1611.3	11.5	McIvor et al. (2009)
	255–2509	1–3	Phillips et al. (2014)
	8–144	1–3	McIvor et al. (2020)
Poplar 'Kawa'	401–3907	1–3	Phillips et al. (2014)
Cypress	16.0-837.4	1–3	Phillips et al. (2015)
Alder	140.0–1268.7	1–3	Phillips et al. (2015)
Cherry	29.6–403.2	1–3	Phillips et al. (2015)

**roots > 2 mm diameter*

et al. (2014) reported information for 1-year post-establishment growth. Data for the subsequent two years of the trial were largely not reported. Only one specimen from one planting type (pole) of each trial clone was left to grow beyond year 1 and was then excavated. Poplar had total root lengths (> 1 mm) of 2.5 km (Veronese) and 3.9 km (Kawa) 3 years after planting (Phillips et al. 2015) (Fig. 5). The exceptional root growth recorded in this study was due to optimal growing conditions, i.e., a flat tilled sandy loam soil with few sub-surface impediments, weed control, and irrigation in summer months when needed. The values recorded exceeded those of any previously published information from similar trials in New Zealand and may have exceeded those grown anywhere. For example, in a trial of poplar trees grown from poles on a lower slope position, McIvor

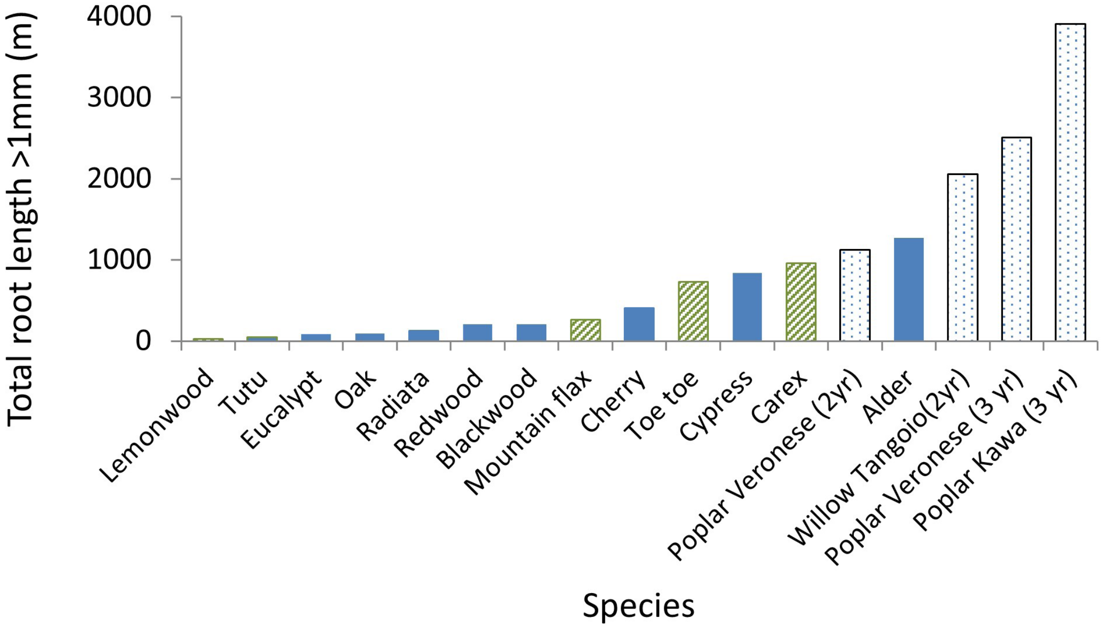

FIGURE 5: Total root length (roots > 1 mm diameter) from Philips et al. (2015 – Figure 9) trial (solid blue bars) compared with existing 3-year-old data from other species trialled at the same site. Mean values except for toe toe, carex, alder, poplar, and willow. Indigenous species (green diagonal shading - Marden et al. 2005). Poplars (V = 'Veronese';K = 'Kawa') and willow (lightly stippled bars – C. Phillips unpublished data). * = 2-year-old data.

et al. (2009) found that 11.5-year-old trees had greater total root length (> 2 mm diameter) (1.6 km) compared to those grown on upper slopes (0.29 km) (Table 3). McIvor et al. (2020) assessed the influence of soil type (3 sites) on root development and below-ground biomass of 1–3-year-old poplar poles and found 3-year-old total root length > 1 mm diameter varied between 64 m and 144 m. Poles growing in pumice soils had greater root lengths than those grown in sandy loam.

Phillips et al. (2013) assessed 1–4-year-old redwood root systems grown at two sites and compared them with similar-aged exotic trees from other studies. Redwood had a similar but slightly less mean total root length of roots > 2mm than radiata pine. However, there were more fine roots in the upper 0.5 m of the soil profile compared with radiata pine trees, which have thicker and fewer fine roots at corresponding distances from the stem. In 4-yr-old redwood trees, roots with diameters less than 10 mm comprised 98% of the total root length. In 4-year-old radiata pine trees, Marden et al. (2016) found 62.4% of the total root length occurred in the 2–5 mm diameter size class and 86.7% in the less than 10 mm size classes.

Root strength, pull-out resistance and direct shear tests

Typical tensile strength of tree roots ranges from 5–70 MPa, and strengths decrease exponentially with increasing root diameter (e.g., Waldron & Dakessian 1981; Genet et al. 2005; Hales et al. 2009). During soil shearing, fine roots tend to break, staying in the same position relative to the soil particles, but coarse roots are often pulled out of the soil without breaking. A combination of dense fine roots in the top layer (where resistance in tension is important) with coarse, deeply penetrating roots crossing potential shear surfaces is the most efficient configuration to stabilize slopes (Reubens et al. 2007).

New Zealand root tensile strength studies of native and exotic species have found similar values to international

TABLE 4: Selection of studies of live root–wood tensile strengths of species tested in New Zealand (largely after Watson & Marden 2004)

Species common name	Mean tensile strength (MPa)	Mean under bark root diameter (mm)	Number of roots tested	Study/reference
Lacebark	51.28	2.11	23	Watson & Marden (2004)
Kowhai	43.72	1.89	28	Watson & Marden (2004)
Mānuka	41.71	2.50	22	Watson & Marden (2004)
	34.24 (37.44)	2.66	62 (22)	Watson & O'Loughlin (1985)
Kohuhu	29.30	1.96	18	Watson & Marden (2004)
Fivefinger	28.16	2.74	52	Watson & Marden (2004)
Rewarewa	26.16	2.64	24	Watson & Marden (2004)
Cabbage tree	26.83	2.35	48	Watson & Marden (2004)
	26.7	0.6–2.0	155 total	Czernin & Phillips (2005)
	24.4	2.0–3.0		
	17.5	3.0–3.8		
Ribbonwood	26.42	2.30	22	Watson & Marden (2004)
Lemonwood	16.44	2.77	24	Watson & Marden (2004)
Tutu	15.68	2.11	29	Watson & Marden (2004)
Karamu	8.38	2.59	13	Watson & Marden (2004)
Southern rata	50.81 (52.06)	2.49	58	Phillips & Watson (1994)
Hard beech	32.57 (44.17)	3.15	97 (15)	O'Loughlin & Watson (1981)
Red beech	36.13	2.64	52	O'Loughlin & Watson (1981)
Kānuka	34.11	2.65	32	Watson et al. (1997)
Kamahi	23.49	3.28	43	Phillips & Watson (1994)
Mountain beech	25.90	2.87	37	Unpubl. data
Douglas fir	27.59	2.84	58	O'Loughlin & Watson (1979)
Radiata pine	17.62	5.3	188	O'Loughlin & Watson (1979)
	15.16	4.2	100	Phillips & Watson (1994)
	13.36	5.8	99	Phillips & Watson (1994)
Poplar	32–47	?	>20	Hathaway & Penny (1975)
Poplar 'Veronese'	19–90 (mean 39.2)	0.9–8.51	123	Watson et al.[xi] reported in McIvor et al. (2011)
Willow (*S. fragilis*)	31.5	0.6–3.8	77	Czernin & Phillips (2005)
Willow (*S. matsudana*)	37.1	?	>20	Hathaway & Penny (1975)

studies ranging from 8–52 MPa (Table 4). In many cases, there are no significant differences between species. It is important that when comparing tensile strengths of different species that tests in the same diameter range are used because there is a general relationship that root tensile strength declines with increasing root diameter, i.e., a negative power function (e.g., O'Loughlin & Watson 1979).

Using only 1–4 mm diameter roots, Watson et al.[xi] ranked common species' mean live root wood tensile strengths. Southern rata, lacebark, hard beech, Veronese poplar, and kowhai rated highest, with radiata pine, lemonwood, tutu and karamu being the lowest. However, in-field, whole root pull-out tests of larger radiata pine roots (≤ 60 mm) showed that, when combined with laboratory root tensile data (Watson & O'Loughlin 1985, Watson & Marden (2004)), the regression relationship in Ross et al.[vii] tended to overestimate the root tensile force for diameters greater than 4 mm (Hiltebrand 2015; Urru 2016; Giadrossich et al. 2020) (Fig. 6). Such field pull-out tests better represent the actual resistance to failure within the soil but roots greater than 60 mm cannot be tested with current equipment.

Lastly, strain gauges clamped to roots were used by Watson (1995) to record *in situ* stresses generated within a tree-root system as the surrounding soil mass was being subjected to an external force. Such whole tree direct shear tests (Wu & Watson 1998) or stump pull-out tests (Mangatu pull-out tests see Phillips & Watson 1994) have also helped understand the force distribution in tree roots under simulated shear conditions or under wind loading. In the latter study, three trees were winched using a bulldozer to simulate the breaking of roots under tension at a landslide headscarp.

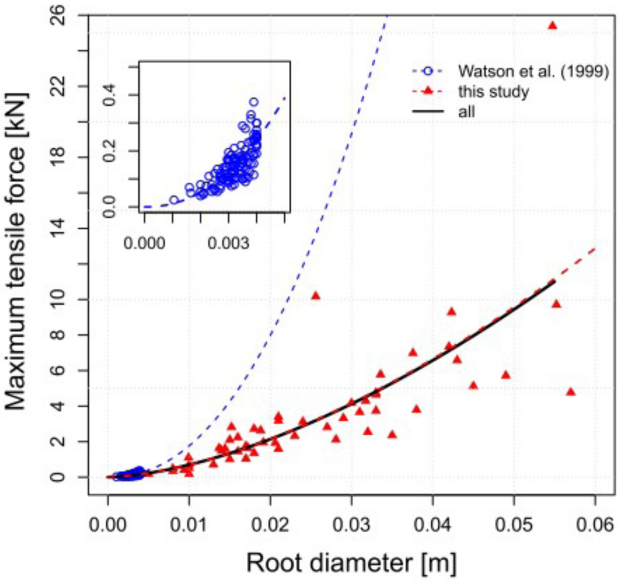

FIGURE 6: Tensile strength of roots as a function of root diameter for radiata pine. Lines indicate the power law regression for different authors and in combination. (Reproduced Figure 3 of Giadrossich et al. 2020).

Root decay following tree removal

Where trees are removed through harvesting or die (burnt in fires, killed by droughts and floods or disease, e.g., kauri dieback or poplar rust), the loss of root tensile strength with time is an important factor to consider, especially where the root reinforcement contributes to a slope's stability. Previous studies (e.g., O'Loughlin and Watson 1979; Watson et al. 1999) have demonstrated the loss of root tensile strength with time for several species and the implications for slope stability. The same authors also describe the general condition of roots following time elapsed since felling, e.g., after 40 months, roots smaller than 3 cm diameter are absent. Table 5 shows selected summary data for radiata pine and mānuka showing loss of tensile strength with time since cutting (O'Loughlin & Watson 1979). After tree removal, radiata pine root systems lose nearly half their tensile strength within the first 15 months, and after 3 years, the large (> 5 cm diameter roots) are in an advanced state of decay (O'Loughlin & Watson 1979). Watson et al. (1997) reported that mānuka root-wood has greater live strength and a lower decay rate than radiata pine and concluded that mānuka would, at least for the first 4 years, provide a clear-felled slope with greater stability than radiata pine.

In general, roots of the faster-growing conifer species such as radiata pine tend to possess lower tensile strengths and decay more quickly than similar-sized roots from the slower growing hardwood species (indigenous and exotic). For temperate climates, the rates of root-wood decay are similar regardless of species or initial root-wood strength (Phillips & Watson 1994; Watson & Marden 2004), declining at about 0.45 MPa month^{-1} from tree removal. This rate of decrease is similar to global observations. In general terms, given the rate of root tensile strength decrease and the live root-wood tensile strength, an estimate of the time taken to lose all or part of the root reinforcement component of soil strength can be determined. To aid forest management, these estimates of root-wood strength decline are usually used in models to assess the likelihood of increased landsliding following forest removal.

Tree stability associated with wind loading

Overview

Wind damage to trees and forests occurs globally with important economic, ecological, social and environmental impacts. The factors influencing wind damage can be classified as either 1) determining wind characteristics or 2) determining the resistance of trees or forests to wind damage (Gardiner 2021). Wind characteristics are determined by climate and topographical effects on wind speed, wind turbulence and gustiness. The resistance of trees or forests to wind is determined by factors operating at the stand scale (such as canopy structure and location and recency of stand edges) interacting with the resistance of individual trees and the vulnerability imposed by root system characteristics, especially those limited by rooting depth.

TABLE 5: Root-wood tensile strength and corresponding mean under-bark diameter of radiata pine and kānuka roots (from Watson et al. 1999). Figures in parentheses are total number of root tests.

Time since cutting (months)	**Radiata pine**		**Kānuka**	
	Mean tensile strength (MPa)	**Mean under-bark root diameter (mm)**	**Mean tensile strength (MPa)**	**Mean under-bark root diameter (mm)**
0 – Living trees	17.62 (188)	5.3	32.45 (64)	4.7
3	14.37 (105)	5.6	–	–
6	–	–	36.36 (74)	5.6
9	12.31 (134)	6.2		
12	–	–	43.13 (80)	5.9
24	–	–	31.64 (100)	6.1
29	3.33 (59)	8.3	–	–
36	–	–	24.20 (67)	7.0
48	–	–	15.53 (87)	6.3

Resistance of individual trees to wind can be either resistance to stem breakage or resistance to uprooting. Partial anchorage failure can also occur resulting in leaning trees, with complete failure resulting in toppling in young trees (Dorval et al. 2016) and uprooting with a root-soil plate in larger trees (Danjon et al. 2005). Toppling is where trees are often not completely uprooted by wind or snowdrift but lean at various angles and continue to grow. The tree's anchorage depends on the architecture of the tree's structural roots, interacting with the strength of the soil in which the tree is growing. A plant transfers the loading forces experienced by the stem into the ground via roots to achieve anchorage. However, even where trees can resist uprooting, they may be damaged or even destroyed by wind through stem breakage or associated processes such as branch and foliage stripping.

Gardiner (2021) suggests that the most important factor in understanding wind damage to trees is to understand that trees are adaptive organisms that acclimate to their (wind) environment. Thus, root structure and allometry are functions of species-dependent root characteristics interacting with environmental factors such as wind and, also importantly, soil. Coutts (1986) reported the relative importance of components for *Picea sitchensis* (Bong.) Carr. being: resistance of windward roots > weight of the root/soil system > strength of the root hinge > soil resistance. Deep taproots are also identified as contributing to the wind resistance of trees (Gardiner 2021) as do sinker roots identified as extending beyond the zone of rapid taper (ZRT) (Dorval et al. 2016). Dorval et al. (2016) reported that for pole stands of *Pinus pinaster* Ait., a large main taproot and large volume of deep roots were the major components that prevented stem leaning. Toppling in shallow soil (< 90 cm soil depth) was avoided in trees with a stocky taproot or large leeward shallow roots. Toppled trees also had a lower relative root biomass (excluding the stump) than straight trees. Yang et al. (2018) found that for 19-year-old *P. pinaster* trees with deep taproots, the dimensions of the taproot, root and soil stiffness and the basal diameter of the shallow leeward roots were the most important factors.

New Zealand studies

Tree resistance to wind damage is particularly important in New Zealand, which is a long narrow island country with axial mountain ranges that lie at right angles to strong prevailing westerly winds. Forest damage is usually the result of winds associated with extra-tropical cyclones or orographic NW winds to the east of the main dividing ranges (Moore & Somerville 1998; Moore & Quine 2000; Martin & Ogden 2006; Pearce et al. 2000). Although indigenous forests occupy about 23% of New Zealand's land area, compared with 7% occupied by exotic plantation forests, research into the interaction of tree roots and wind resistance has largely focussed on plantations of exotic trees. A review of wind damage and response in New Zealand forests suggested a lack of consistent methods combined with poor spatial coverage made it difficult to identify the influence of species x environment interactions on root structure and allometry (Martin & Ogden 2006).

New Zealand research has tended to focus on the toppling of young plantation stands of radiata pine less than six years of age or between 1 and 3 m in height (see Moore et al. 2008). A permanent lean of ≥ 15° in juvenile radiata pine is likely to result in some degree of stem distortion at maturity (Mason 1985; Watson & Tombleson 2002) which affects the future value of the tree. Watson & Tombleson (2004) summarised the tree root growth responses to wind exposure in New Zealand. They found that wind-induced stresses concentrate at the base of a tree and are transferred via the near-stem roots to the soil. To dissipate this stress, biomass is allocated to those near-stem roots, which respond by increasing diameter. The biomass and architecture of near-stem roots vary according to tree age, wind exposure, and the predominant wind direction.

As observed from many overseas studies, soil properties are also known to strongly influence root morphology and hence tree stability. In New Zealand, Chavasse (1969) concluded that toppling was most likely to occur on sites with poorly-drained wet soils and strong turbulent winds. Moore (2000) measured the maximum resistive bending moments for 164 radiata pine trees spanning a range of ages and sizes growing on six different soil types and found that failure type was closely linked to soil type. Ninety-two per cent of trees failed by uprooting on non-cohesive soils but only 11% failed by this mode on clay soils. Root plates were measured on 86 of the 116 trees that failed by uprooting, and root plate diameters ranged between 1.2 and 6.7 m and the rooting depth between 0.2 and 2.1 m. No additional information was given on root characteristics.

Apart from soil drainage and cohesiveness, other key soil properties known to lead to shallow root systems and reduced tree stability include impeded drainage or shallow soil profiles over impervious rock and gravels (Ray & Nicoll 1998; Ross et al. 2004). In such situations, cultivation has been used to improve the development of roots of planted trees and reduce toppling in parts of New Zealand. Mason & Cullen (1986) found that soil ripping, with or without soil mounding, reduced toppling incidence. Trees planted on ripped sites had better root form and vertical root growth than trees growing on unripped sites (Mason et al. 1988). Similarly, Somerville (1979) found that the vertical distribution and form of roots of 11.5-year-old radiata pine trees were improved by ripping—even though the amount of below-ground biomass remained relatively unaffected by this treatment. Ross et al.[vii], also report ripping the clay-rich subsoil Moutere gravels at Golden Downs to 65–70 cm depth improved root development into loosened subsoil, with trees in ripped plots less susceptible to windthrow. Other cultivation methods, however, can have the opposite effect and increase the risk of toppling. Trees planted on sites that were only disc-cultivated or rotary-hoed were more likely to topple because the subsoil remained compacted, which inhibited vertical root development, while the cohesiveness of the topsoil was reduced (Mason & Trewin 1987). Similar results were reported by Ross et al.[vii], where cultivation did not increase the depth to the root limiting layer of a (Wharekohe) Podzol and an Ultic Soil and observed root volume was consequently unchanged (Table 6).

Although soil properties are clearly important to tree stability, research has also shown that susceptibility to toppling is also influenced by planting stock type and planting methods. The process of raising trees in a nursery and subsequent out-planting can result in a distorted root system, which can increase the risk of toppling (Chavasse 1978; Moore et al. 2008). Mason (1985) excavated roots of 49 pairs of toppled and stable radiata pine trees and using the Menzie's scores for both taproot and lateral roots (Menzies et al. 1991), concluded that straight-grained taproots and sinker roots reduced the likelihood of toppling. Physiologically-aged cuttings were also shown to have stronger, stiffer root systems compared with seedlings (Menzies et al. 1991). Gautam et al. (2003) also found that root:shoot ratio and lateral and vertical root biomass were greater by 1.5, 2.3 and 6.1 times, respectively, in cutting-grown than in seedling trees aged 3-4 years old. Fractional allocation of root biomass to lateral and vertical roots was higher in cutting-grown than in seedling trees by 1.1 and 2.6 times, respectively, while allocation to the root core was 1.4 times higher in the seedlings than the cutting-grown trees. In the same experiment, toppling incidence after two years was 86% for seedlings and 10% for cuttings in the plots with complete weed control. However, these findings contrast with those of Watson & Tombleson (2004), who compared bare-root seedlings and bare-root cuttings of radiata pine at three ages (11, 27, and 36 months). They found that by 36 months, a greater portion of biomass had been allocated to the near-stem lateral roots of bare-root cuttings than bare-root seedlings. The authors suggested that this was likely to be related to a wind-induced adaptive growth response and concluded that as only a portion of the root system, i.e., the near-stem roots, contribute to tree stability, the use of root:shoot ratio as a primary indicator of tree wind-stability ranking could be suspect. Such differing conclusions may occur because the process of uprooting is more complex than stem breakage due to the interactions between root systems and the soil. While the role of near-stem lateral root biomass versus root:shoot ratio or vertical root biomass and depth remained inconclusive in New Zealand studies, subsequent overseas studies have resolved this, finding that stump excluded, toppled trees had a lower relative root biomass (Dorval et al. 2016).

Lastly, even if nursery-raised trees have good, well-structured root systems and the site has been cultivated appropriately, careless planting can result in deformed root systems leading to tree instability (Trewin 2003). Trewin (2003) asserted that most toppling and subsequent butt-sweep were the result of roots being bent up or swept sideways as they were placed into the planting hole, preventing the development of straight vertical and sinker roots. As a result, the roots continue to grow in this position providing little anchorage for fast growing trees like radiata pine.

In summary, both New Zealand and overseas studies have attributed wind stability to different components of root morphology. These in turn arise from the way in which the tree adapts to its local environment including the soil in which they adapt to growing in. It is also clear that the contribution of root characteristics to the superior wind resistance of radiata pine cuttings compared with seedlings is now well-accepted within the New Zealand plantation forestry sector. Management techniques to improve root architecture and reduce toppling in New Zealand include the use of 'physiologically aged' cuttings (Gautam et al. 2003) or establishment by direct-seeding rather than planting; cultivation to facilitate correct planting and unimpeded root development (Mason & Cullen 1986; Mason et al. 1988; Somerville 1979) and contractor training and quality control to ensure that trees are carefully and correctly planted (Trewin 2003).

TABLE 6: Summary of cultivation effects on rooting patterns and wood production for 6 North Island trial sites. Reproduced from Ross et al. (2004). + = slight increase or effect restricted to topsoil; ++ = marked increase; n.s. = not significant.

Trial No.	Soil (NZ) classification	Effect of cultivation on potential rooting volume	Effect of cultivation on observed root volume	Effect on root volume	Depth to root-limiting layer in uncultivated soil (cm)	Depth to root-limiting layer in cultivated soil (cm)	Notes on probable limiting factor
Central Plateau Trials							
RO1063	Pumice soil	+	+	Nil	100 +	100 +	Coarse pumice
RO1964	Pumice Soil	++	++	Nil	30	70	Welded pumice
W361/2	Allophanic Soil	++	+	+ n.s.	100 +	100 +	Silt loam subsoil
North Island Trials							
AK578/2	Ultic Soil	+	n.s.	Nil	40	40	Clay subsoil
AK578/1	Podzol	++	n.s.	- n.s.	30–40	30–40	E / Bhm pans
AK662	Ultic Soil	+	+?	+ n.s.	15	30	Erd densipan

Soil reinforcement and slope stability modelling

Overview

It is beyond this paper's scope to review the literature on soil reinforcement by roots and how trees contribute to slope stability. In addition to the references cited in the introduction of this paper, we refer the reader to Norris et al. (2008), Stokes et al. (2013, 2014), Pollen-Bankhead et al. (2013), Schwarz et al. (2012, 2013), Saint Cast et al. (2019), Giadrossich et al. (2019) and Masi et al. (2021) for further background information on soil reinforcement and some recent modelling advances. Mechanical strengthening of soil by a tree occurs because of reinforcement by the tree's roots and is due to the root's tensile strength, frictional, and adhesion properties. Soil is strong in compression but weak in tension; conversely, plant roots are weak in compression but strong in tension. When the two are combined, they produce a matrix of reinforced earth, stronger than the soil or the roots separately. Quantifying the reinforcing effects of tree roots within soils and evaluating hillslope stability using geo-mechanical, numerical or statistical models relies on a realistic representation of the characteristics of a tree's root distribution within the hillslope and the mechanical strength of those roots. While the general mechanisms of how tree roots contribute to slope stability are well known (see introduction), understanding of detailed mechanisms (for example, root-soil cohesion at the microscopic level) is not well advanced. However, three mechanisms are important for how roots contribute to the stability of a slope (O'Loughlin & Zhang 1986):

1. Providing a reinforced surface layer of soil usually not more than about one meter deep, which provides a type of membrane strength or lateral-acting strength that holds the underlying regolith in place — lateral roots.
2. Bonding unstable soil mantles to stable subsoils or bedrock where roots can extend across potential shear/failure planes and into more stable materials can provide a stabilising effect on an unstable upper soil mantle — vertical roots.
3. Providing localised centres of substantial reinforcement close to the tree where larger structural roots and central root bole act as supporting buttresses.

One of the main issues in considering root reinforcement in slope stability modelling, particularly of large areas, is the difficulty of evaluating the spatial variations of model parameters. The spatial distribution uncertainty of root reinforcement that limits regional slope stability models is a well-known problem affecting other physical parameters such as cohesion, friction angle, and hydraulic permeability. There is often high spatial and temporal variability in root reinforcement even within the same species, increasing the uncertainty in models. However, there is increasing international effort to address this so that distributed applications and slope and regional scale modelling that includes root reinforcement can advance (Masi et al. 2021). Many of these approaches focus on relating remotely-sensed values of above-ground vegetation indexes and relating them to spatial patterns of root cohesion or root biomass through various statistical methods.

New Zealand approaches to root reinforcement or slope stability models and applications using New Zealand data

Excluding surrogate approaches or indicators to assess soil root reinforcement such as via allometric and regression relationships, the earliest assessment of a tree roots contribution to slope stability in New Zealand used an infinite slope stability model based on Coulomb's law (which relates a soil's strength or resistance to failure to the forces driving failure (functions of soil cohesion, soil friction, and normal stress)) (O'Loughlin 1974). Using soil data collected from a natural slope in Canada, it was demonstrated that the stability of the slope depended heavily on the additional strength imparted by the tree root network during storm periods when the slope was saturated, and therefore, deforestation may cause changes in the stability of steep slopes. Early studies of tree roots in New Zealand suggested that the root systems of exotic conifers began to influence slope stability substantially between 5 and 10 years after establishment (O'Loughlin 1984) at typical planting densities of 1000–1500 stems ha^{-1}. At this stage, individual tree root systems have developed a substantial set of lateral structural roots extending up to 4.0 m from the stump. In New Zealand, 4.0 m is a common distance between planted rows, so that roots between trees in different rows would overlap between 5 and 10 years after establishment to provide a reinforced network of lateral roots.

Stability analyses of vegetated hillslopes show that the stress-strain behaviour of soils with roots is quite different to soils without roots (fallow soil). Results of *in situ*, direct shear box tests (O'Loughlin & Ziemer 1982; Ekanayake et al. 1997) have shown that the increased peak shear stress of soils with roots produces a broader and flatter-shaped strength vs displacement curve compared to fallow soil. Such soils can resist the forces that would cause failure (i.e., a landslide) on a hillslope. Most stability analyses of vegetated hillslopes are usually carried out by the limit equilibrium (LE) method, where shear displacement or strain is not considered. In such cases, the safety factor could be underestimated for soils with roots. Ekanayake & Phillips (1999) developed an approach within a stability analysis to account for the ability of soil with roots to withstand strain. This stability analysis considered the energy consumed during the shearing process of the soil-root system rather than the ratio of the shear forces of soils with and without roots. It used characteristics of the shear stress-displacement curve of a root-soil system obtained from in situ direct shear tests under simulated overburden pressure and pore-water conditions. The approach is limited to vegetated hillslopes where the stability analysis can be approximated by a simplified infinite-slope model such as in typical New Zealand hill country where shallow landslides are common.

Ekanayake et al. (1997) found slope safety factors for radiata pine stands in the first 9 years after establishment would be lower than for equivalent-aged stands of fully-stocked regenerating mānuka under similar conditions due to significantly higher stand densities of mānuka. Parity in safety factors between the two species occurred about the 16th year because of the increase in the annual rate of root biomass production in radiata pine while that of mānuka remained relatively constant. Further, radiata pine exhibited strong vertical-root development with both the taproot and sinker roots growing to greater depths resulting in greater root cross-sectional area at about 1 m depth (approximate failure depth of shallow storm-initiated landslides) (Fig. 7). Similarly, the effects of species, planting density and rainfall thresholds on shallow landsliding underpinning planting guidelines in erosion-prone regions were examined (Phillips et al.[vi]).

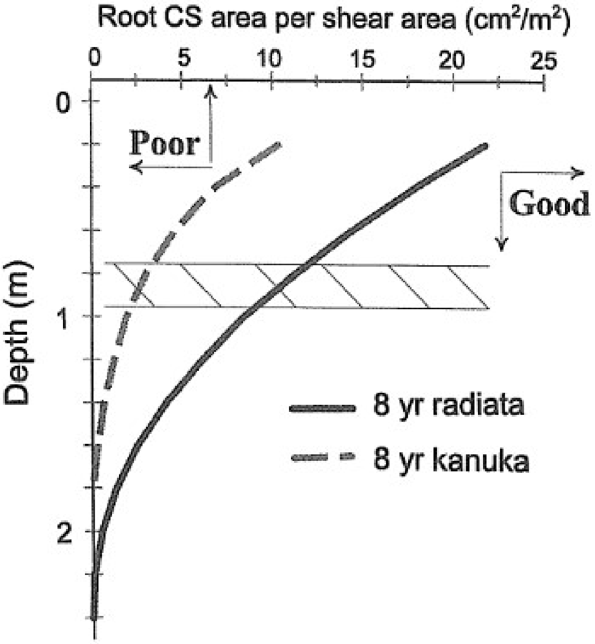

FIGURE 7: Root cross-sectional area per shear area versus root depth for 8-year-old radiata pine and 8-year-old kānuka (Phillips et al. [vi]). The hashed area represents typical depths of shallow landslides on East Coast hill country.

Root-growth data (Watson & O'Loughlin 1990) and canopy-development data (Grace et al. 1987) were used to generate a site-occupancy model (Phillips et al.[vi]). This model used time-series data of the diameter of root systems and canopies (crown) of radiata pine of known age projected onto the ground as circles for different planting density and silviculture scenarios. Site occupancy equalled 1 when the perimeters of adjacent root systems or tree canopies came into contact. Site occupancy of < 1 indicated that open spaces remained between adjacent trees. Growth rates for the period 1 to 7 years were estimated as root-growth data at this time were available only for trees ≥ 8 years old. The model was used to evaluate the timing of site occupancy by lateral roots at different planting densities to inform planting guidelines (e.g., Phillips et al.[vi]). Similarly, root length data (root spread) from a trial of young New Zealand trees and shrubs were used to develop a simple model (Phillips et al. 2011) to account for the spatial occupancy of a planting site by roots, and by implication, their potential strength contribution to soil reinforcement. It was used to calculate the effective root spread radii of different indigenous species and compare their effectiveness at different planting densities. Tutu and cabbage tree followed by lemonwood were the best performers, with the former reaching 100% lateral root site occupancy in 3.5 years at 1 m x 1 m planting density.

Watson et al. (1999) brought several lines of research understanding together to create a generalised conceptual model of changes in relative root reinforcement in radiata pine and kānuka when slopes are clearfelled or removed from erosion-prone slopes. The implications of reduced root reinforcement for slope stability during extreme landslide-triggering rainfall events were evaluated. They concluded that slopes with clearfelled radiata pine are potentially more vulnerable to the stresses promoting instability, at least in the earlier years. The conceptual model followed that of Sidle (1991) and has become known as the 'window of vulnerability' (O'Loughlin 1985; Phillips et al. 2012; Phillips et al. 2015).

Hawley & Dymond (1988) presented a method for calculating the effectiveness of trees in reducing the incidence of shallow landslides in hillslopes based on the assessment of landslide scars and proximity to widely spaced trees using digital imagery. A graph of the average fraction of ground eroded versus distance from a tree is derived. The average radius of influence of trees and the area of ground saved from sliding by the trees are deduced from this. The method predicted that if trees had been planted on a 10-m grid with a 100% establishment rate, storm damage would have been reduced by at least 70% (this became known as the J factor and has been used in sediment budget models to assess the role of spaced trees in reducing long term average sediment yields (Dymond et al. 2016). More recently, Spiekermann et al. (2021) quantified the influence of individual trees on slope stability using tree influence models (TIMSS – empirical tree influence models on slope stability) for several common species found on New Zealand pastoral hill country (poplar/willow, kānuka, conifer, eucalyptus). The approach uses high resolution multi-spectral imagery to quantify the influence of an individual tree on past landslide activity. Using inductive inference, the tree influence models largely agree with the shape and distribution of existing physical root reinforcement models and confirms that influence on slope stability declines rapidly with distance from the tree stem.

Two root distribution datasets for 'Veronese' poplar (McIvor et al. 2011; Phillips et al. 2014) used to calibrate Schwarz et al.'s (2010a) model were then used to estimate effective root reinforcement for widely spaced poplar trees, and calculations of slope stability were made within a limit equilibrium framework (Schwarz et al. 2016). The study concluded that planting density between 160 and 330 stems ha^{-1} (corresponding to 8.0 m and 5.5 m distance between trees) would assure significant root reinforcement for slope stabilisation (> 2 kN m^{-1}) and reduce the volume of triggered landslides by up to 100%. In ideal growing conditions, 100 stems ha^{-1} of trees with DBH > 0.15 m would create sufficient root reinforcement. However, the modelling results also suggested planting at a higher density to hasten slope stabilisation and thinning later as canopies and roots develop. Douglas et al. (2011) modelled landslide reduction in wide-spaced poplar trees by considering the location of shallow landslides relative to their distance from existing trees and suggested they were effective in reducing shallow landslide occurrence across the density range of 32–65 stems ha^{-1}, though the trees in the study area were 43–52 cm DBH, i.e., significantly larger than indicated by Schwarz et al. (2016).

Phillips et al. (2015) compared the lateral root spread of exotic species grown in a field trial, including alder, cherry, Tasmanian blackwood and redwood, with reported values for indigenous riparian species (Marden et al. 2005), mānuka (Marden & Lambie 2016) and radiata pine at a similar age (Watson & Tombleson 2002, 2004; Marden et al. 2016). The conclusion drawn was that the species with larger root system dimensions would provide earlier soil-root reinforcement and thus be more effective in mitigating the initiation of shallow landslides. Similarly, root depth was used to indicate species' potential for stabilising deeper-seated forms of erosion (e.g., rotational slumps and larger earthflows). Tap-rooted species (e.g., kauri, mānuka) have the potential to develop thicker and stronger roots able to penetrate across the basal shear plane to provide a deeper level of reinforcement, albeit only for the small deep-seated failures, than would plate-rooted species.

Model development in recent years has focussed on the contribution of lateral roots to slope reinforcement. However, the findings of Marden et al.'s (2016) study suggest that for species which develop vertical tap and sinker roots such as radiata pine, and where these comprise a significant proportion of the total root biomass, their contribution to slope reinforcement and tree anchorage is likely to be significant and should therefore be included in future model development.

Techniques for modelling root-soil interactions have improved significantly over the last 5-10 years with the introduction of fibre-bundle models to the study of root reinforcement, allowing the mechanics of root breaking, stretching, compression, and pull-out to be modelled successfully. Root-reinforcement modelling has shown that roots can be significant in stabilising slopes and streambanks—affecting both the timing and magnitude of mass failure events and the geomorphic processes that cause them (Pollen-Bankhead et al. 2013). However, one of the limiting factors for quantitative analysis is the lack of field data and how models deal with the temporal and spatial heterogeneities in soil physical properties, soil moisture and the variations in root-soil interactions between and within species.

Discussion and Conclusions

We undertook a retrospective 'review' of New Zealand tree root research focusing on soil reinforcement and its application for erosion control, slope stability assessment, and understanding wind firmness and tree stability in plantation forests. Not surprisingly, investigations into the root systems of New Zealand's indigenous trees and some of its key exotic species have highlighted differences both within and among species and across different soils/landscapes. While the data are limited for individual species, these empirical data have allowed some general statements to be made. These include:

1. Exotic tree species generally outperform indigenous tree species in terms of their

contribution to soil reinforcement and for most empirical metrics other than root tensile strength.

2. As above-ground tree characteristics vary between species, so do their below-ground root systems. But for some metrics, the differences between species are not significant, and for certain modelling purposes, a tree is a tree.
3. A combination of lateral and vertical roots in a tree's root architecture provides the best soil reinforcement and contribution to resist rainfall-triggered soil erosion and climate damage. Where a tree does not develop deep sinker or tap roots, strong development of lateral roots can still provide adequate root reinforcement against wind and erosion. The exception is the need for strong vertical roots to combat landslides where the failure plane is deep in the soil profile.
4. Key mechanical properties of roots are root tensile strength and shear resistance. These influence the resistance of roots to the two failure modes of roots subject to landslides and damaging climatic factors such as wind or snow.
5. Apart from coppicing species, felling a tree leads to its death and causes a loss of root tensile strength (and soil reinforcement) with time.
6. The time (years after establishment) required to attain an adequate soil-root reinforcement level depends on planting density and growth rate and is species-dependent and is influenced by soil characteristics and site stress.
7. Root systems influence the mechanical and hydrological behaviour of soils sufficiently to mitigate initiation of shallow landslides. This root system influence is a function of plant species (indigenous vs exotic) and type (evergreen vs deciduous) and plant survival rate in sufficient numbers to provide full soil-root occupancy. However, landsliding is also governed, more so, by environmental factors which can vary considerably within and between sites.
8. Soils have a significant influence on root architecture by controlling rooting depth through features such as pans, water tables/anoxic zones, and depth to rock. Soils also influence toppling (through depth but also support offered), and on root biomass through links to nutrients (C:N, P), and total particle size (Watt et al. 2008). Cultivation practices that increase limited rooting depth reduce tree toppling.
9. The need to explain and predict the role of tree roots in mitigating landslides and other soil erosion has led to the development of models to predict the effects of tree species, silviculture (especially spacing) and site on root reinforcement of soils. However, such models are limited by two factors. Firstly, field data are sparse, since root studies are expensive and time-consuming, and observations (N) are relatively few. Secondly, models must accommodate temporal and spatial heterogeneities in edaphic properties and climate as well as variations in root-soil interactions.

From the early beginnings of observations of toppled trees and shallow excavations exposing lateral surface roots, the last 50–60 years have seen a small but enthusiastic group of researchers improve our understanding of the root systems of many common New Zealand trees and shrubs and the role they play in reinforcing soils, reducing erosion, and reducing tree topple. From excavating whole tree root systems to assessments of root architecture and morphology to more detailed field and laboratory studies of individual roots, the advancement in our understanding has mirrored, to a large degree, international trends for interest in: 1) how vegetation influences the mechanical and hydrological behaviour of soils and on erosion processes, particularly shallow landsliding; 2) how root systems influence wind stability of forests, especially planted forests; 3) how cultivation practices change root patterns, and 4) the contribution of roots to forest biomass and below ground sequestration of carbon.

In recent years, largely because of increased interest in the subject and increasing computing power, there has also been significant growth in the development of a range of models and approaches appearing in the international literature (e.g., see Masi et al. 2021).

The excavation of whole plants in New Zealand root studies has provided valuable insights (and data) into interspecies differences in root architecture (dimensions), root sizes and biomass and their distribution relative to soil depth and distance from the stem. Such data are necessary to underpin planting guidelines for erosion-prone terrain in New Zealand, particularly the selection of appropriate species mixes and planting densities. Furthermore, they contribute to developing and testing models to assess the period (years after planting) juvenile plantings are likely to remain vulnerable to rainfall-triggered shallow landslides and from bank erosion, informing catchment management strategies to limit erosion. Such data have also helped forest managers understand and reduce wind damage to juvenile plantation trees.

Recommendations for future research

Since the publication of Phillips and Watson's (1994) root bulletin nearly 30 years ago, our understanding of tree roots and their contribution to soil reinforcement and slope stability in New Zealand has increased. However, despite these gains, many of the research needs expressed by Phillip and Watson (1994) have still not been fully met. This result seems to have broadly mirrored the international experience. At the same time, there also appears to be a growing interest in root research (Masi et al. 2021), particularly in countries such as China and other non-English-speaking countries – this activity perhaps reflected in the wider number of journals and publications now available and accessible. Much of this research interest focuses on modelling (Masi et al. 2021) with a trend towards expanding from slope to catchment and regional scale — although estimating root reinforcement at the regional scale remains challenging and is the key limitation for spatially-distributed slope stability analysis.

Several recent papers have outlined research needs in the wider bio-, eco-, and soil-bioengineering fields (e.g., Stokes et al. 2014, Rey et al. 2019, Masi et al. 2021). Invariably, they all call for more data and improvements in dealing with the challenges of spatial and temporal variability in the species-specific characteristics of tree roots and in factors such as soil and soil hydrology and how these affect root reinforcement. Research into plant species not previously investigated and studying those that have been researched under different environmental conditions is also a globally pressing need. The close linkage between soil hydrology/soil moisture and the behaviour of roots (e.g., their tensile strength) is another need that requires addressing.

Despite efforts to date, species-specific growth performance data for mature and juvenile trees of many New Zealand indigenous species remain elusive, particularly in relation to below-ground attributes for mature trees. Time-series baseline data on plant growth rates need to be collected across a range of the site conditions known to influence plant growth. This need is becoming increasingly important as the calls for closed-canopy forestry, reforestation with indigenous species, and dealing with declining biodiversity and environmental degradation increase (e.g., Norton & Forbes 2013; Forbes et al. 2019; Payn 2021; Weaver 2021).

In addition, root data need to be collected in a format suitable for inclusion in slope stability and/or soil reinforcement models (e.g., Schwarz et al. 2010b), many of which suffer from a paucity of, and lack of consistency in, the types of data collected to date. The description of root systems and their analysis in New Zealand has largely focused on spatial distribution as a function of diameter. Applying 3D data capture coupled with both statistical and finite element modelling used in other countries is likely to yield further understanding and help discriminate species' root systems to underpin wider model development and application. Understanding what tree species to use, where to use them and how many (density) to establish to attain maximum root reinforcement, remain key needs for land practitioners. Data-supported models will go some way to support such needs. If landslide hazard mitigation can be accomplished alongside enhancing local biodiversity through tree plantings of indigenous species, then so much the better.

Understanding the impact of forest structure disturbances due to silviculture, wildfires, or disease on root reinforcement is also an emerging topic where further studies are needed. Much of this type of information is needed to support statutory policies or regulations, most of which currently rely heavily on qualitative knowledge. Quantitative evidence or better methods to identify performance thresholds of interventions (i.e., targeted planting or use of bio-engineering approaches) is increasingly seen as being critical, particularly in litigious jurisdictions. In much the same way as there is a need to understand the spatial and temporal characteristics of plant species and the environments in which they grow, there is also a need to understand the implications of interventions at the catchment and larger scales both in terms of hazard management but in broader environmental terms, e.g., impacts on catchment hydrology (groundwater) and on ecological connectivity or other ecosystem services. These issues can only be resolved with a greater level of discussion between the research community and natural resource managers.

Lastly, while there will continue to be an academic interest in root studies, an ongoing and well-identified need is the development of practical tools that land managers can use to understand a tree's or forest's influence on soil reinforcement and slope stability. These tools will allow the most erosion-susceptible parts of our landscapes to be appropriately targeted with the right forest vegetation (species, amount, density). This is a pressing need as changing climate is affecting the nature of many biophysical hazards (landslides, floods, wildfires, strong winds, pathogens and pests). The role of vegetation in helping manage these hazards (or contributing to them) is thus crucial for understanding how we humans interact with our physical environment (e.g., Griffiths et al. 2020; Dudfield et al. 2021; Mickovski 2021).

List of abbreviations

DBH – Diameter at Breast Height
RCD – Root Collar Diameter
TIMSS – Tree influence model for slope stability

Competing interests

The authors declare there are no competing interests.

Authors' contributions

MB and CJP conceived the idea for the paper. CJP was the primary author. MB conducted literature searches and contributed information and writing the section on wind firmness and tree stability. MM and SL contributed to sections of the review. All authors read and approved the manuscript.

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