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TREE SPECIES PERFORMANCE AND SLOPE STABILITY

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ABSTRACT

Root systems of 13 radiata pine (*Pinus radiata* D. Don) and 15 kanuka (*Kunzia ericoides*), representing three age classes of trees from the East Coast region, North Island, New Zealand, were hydraulically excavated. Each root system was weighed and measured to obtain comparative information on the changes in root architecture (morphology) and root biomass with time. For both species, rates of decline in root-wood strength were determined and compared, along with tree root performance, against the probability of major storm events.

Annual rate of root production of kanuka (2.2 t/ha) exceeded that of radiata pine (1.1 t/ha) for the first 9 years of growth. Live kanuka root-wood is approximately twice the strength (34.2 MPa) of that of radiata pine (17.6 MPa), and after felling took twice as long to lose its soil reinforcement properties. It was estimated that if kanuka was replaced by another tree species, there would be a 3-year period of inadequate tree root protection, which represented a 60% chance of a major storm event. Similarly, radiata pine would leave a 5-year period of vulnerability, and an 80% probability of a major storm.

BACKGROUND

In 1988 a large cyclonic storm affected the East Coast region of the North Island, New Zealand. Rainfall intensities were up to 900 mm in 5 days and the storm had a return period exceeding 100 years. East Coast hill country, the most-affected area, is particularly susceptible to erosion as the original forest soils are underlain by severely crushed, sheared and distorted bedrock. In response to the storm the Government set up a scheme in which marginal pastoral land in the more erosion-prone areas would be converted, over a period of 10 years, to commercial forestry plantations, dominated by radiata pine.

Part of the scheme involved incentives for clearing regenerating indigenous scrub, in which kanuka forms a large component. Stands dominated by kanuka occur on approximately 140 000 ha of erosion-susceptible hill country, predominantly on the east coast of both the North and the South Island. Over recent decades large areas of kanuka have been cleared for forestry and pastoral development. In some steepland locations the frequency of translational landslides (defined in Varnes 1978) have increased. Particularly in areas where shallow-rooted pasture grasses have provided less than adequate slope protection, especially during periods when the soils are at near or full saturation.

In anticipation of the escalation of afforestation and to address the soil conservation and erosion problems facing the East Coast region, a research project was initiated with the aim of developing effective stabilisation techniques for unstable and degraded slopes. Species performance of kanuka and radiata pine was compared by investigating rates of change in root biomass and architecture, site occupancy (i.e., when roots from adjacent trees start to overlap) and soil-root reinforcement, and their modification of the soil-water regime.

The paper will explain the field investigation and give preliminary results of the study.

SITE DESCRIPTIONS

Study sites are located in the East Coast hill country, east of the Raukumara Range, North Island, New Zealand, (Fig. 1). The topography varies from steep dissected slopes (25-40°) on hard fine-grained sandstones, to gentle terrain (12-15°) of clay-rich shales (Watson & O'Loughlin 1990). The clay-rich shales are generally more erosion prone.

Sites are similar in terms of their disturbance history. Podocarp-hardwood forest was clearfelled to create farmland during the latter nineteenth century. Increased erosion coupled with productivity decline, followed 70-100 years of intensive grazing, has resulted in changes to exotic forestry or abandonment. The radiata pine used in this study were located at Mangatu forest in the headwaters of the Waipaoa and Mangatu Rivers. The stands of kanuka were growing on poorly utilised farmland, north of Gisborne, that in part had been allowed to revert back to indigenous scrub.

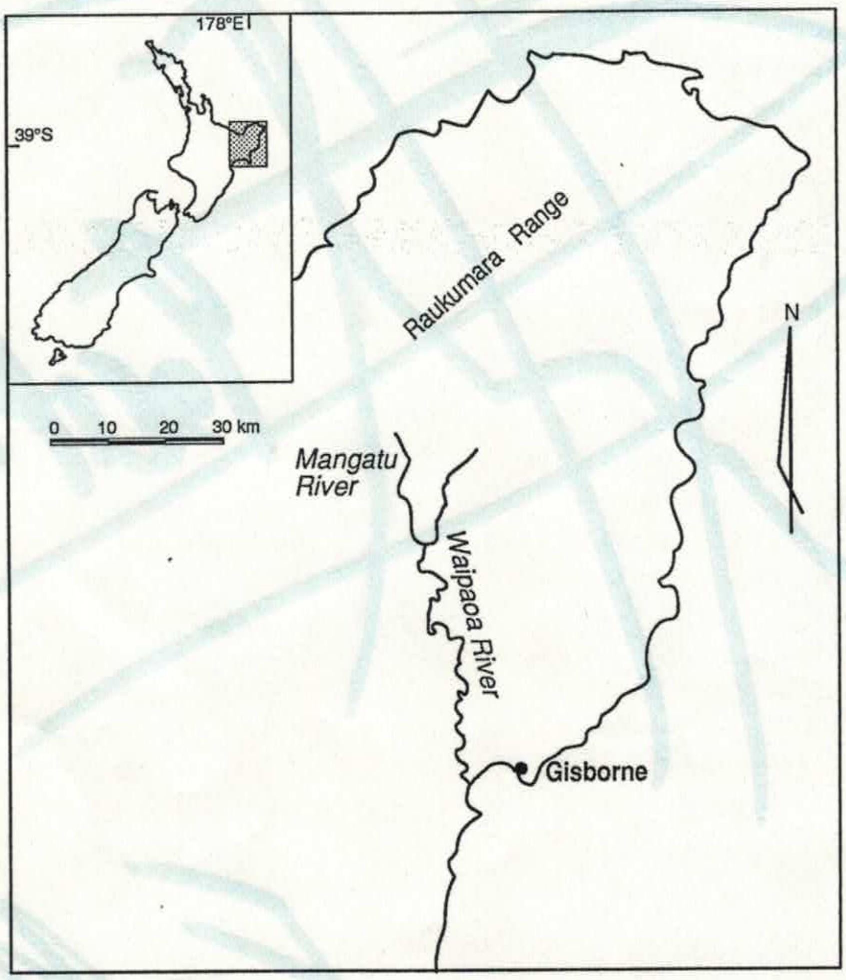

Fig. 1 Location map of study area

CLIMATE AND FLOOD CHARACTERISTICS OF THE EAST COAST REGION

The climate is temperate marine, with warm dry summers and cool wet winters. Mean annual rainfall at lower elevations (Gisborne airport, Station No. D87692, altitude 4 m) is approximately 1080 mm, increasing to 2100 mm at the higher elevations, (Mt Arowhana, Station No. D87181, altitude 732 m) (New Zealand Meteorological Service 1984).

The region has a history of extreme floods, generally resulting from high intensity rainfall during infrequent tropical cyclones. These storms have been a major feature contributing to the unstable nature of the hill country, east of the Raukumara Range. In all there have been 29 extreme floods of the Waipaoa River, (catchment area 1580 km^2), during this century (Kelliher *et al.* 1994).

METHOD

Root systems of 28 sample trees, 13 radiata pine and 15 kanuka, (Table 1) were excavated using high pressure water. The technique required selection of trees growing on slopes steep enough to allow easy flow of the sluiced material away from the excavation site. Two types of nozzles were used, one supplied a narrow high-pressure jet which was used to remove the bulk of the surrounding soil, the other delivered a broad spray which removed the remaining soil from the finer roots. This enabled a 100% recovery of roots >2 mm diameter. Roots less than 2 mm diameter were not considered to be major structural contributors to slope stability and were not included in the assessments.

Sluicing began far enough downhill from the stump to ensure that as the excavation proceeded up slope it was of sufficient depth to expose the deeper vertical roots. As the root systems were exposed, they were propped in position so their architecture could be mapped and measured in detail.

Each root system was cut up and sorted into the following diameter classes, then weighed and measured.

Small structural roots	2 - 10 mm diameter
Medium structural roots	10 - 20 mm diameter
Large structural roots	20 - 50 mm diameter
Very large structural roots	50 - 100 mm diameter
Course structural roots	>100 mm diameter
Central root bole at base of stem	

Field root samples from the kanuka sites were dried to a constant weight at 70°C in a forced-air drying oven to obtain % moisture loss. This was then used to calculate the oven dried weight of each root size class. The radiata pine root systems were allowed to air dry for up to 6 months before being weighed and measured.

RESULTS AND DISCUSSION

Root Morphology

Kanuka: The 6-year lateral roots were largely confined to the upper 0.2 m of soil. For the three age classes (Table 1) the lateral roots of the majority of the trees were distributed asymmetrically around the stump, growing predominantly, up and across slope. The asymmetrical rooting pattern of the 16-year trees was largely due to frequent branching and consequent rapid taper, which produced dense fibrous roots on the downhill side of the trees. In all classes the longer roots grew within 0.1 m of the ground surface. Mean maximum and maximum root lengths (measured to a minimum root diameter of 2 mm) are given in Table 1. By 32 years the lateral root systems were well developed, with the larger roots at times intertwining with roots of adjacent trees. Approximately 97%, 90%, and 90% of the mass of the 6, 16, and 32-year root systems, respectively, were within 1 m of the stump.

Vertical roots of all age classes were poorly developed, with strongly tapered taproots that often branched. For the 32-year root systems, growth was in part restricted by an increasing number of angular stones with depth. Approximately 95% of the root mass of the 6, 16, and 32-year root systems was confined to the top 1.0 m of soil. Mean maximum and maximum rooting depth are shown in Table 1. The majority of vertical roots originated from directly below the stump, although for all age classes a secondary group of vertical roots (sinkers) grew from the underside of the main laterals. Initially they were small, growing to depths of 0.6 m and from up to 0.4 m from the stump. At year 16, though depth and spread had not increased, they were more numerous and of larger diameter, and by 32 years the sinkers were growing to depths of 0.9 m and had a spread of up to 1 m from the stump.

Table 1. Mean site parameters, mean age, number and size of sampled trees and dimensions of their root systems.

	Radiata Pine				Kanuka		
Mean age (yrs.)	8	16	25		6	16	32
No. trees	5	5	3		5	5	5
Slope of site (°)	26	22	15		28	32	23
Site aspect (°)	210	335	20		60	345	280
Mean tree height (m)	9.5	21.1	30.4		6.1	6.7	13.6
Mean DBH (mm)	170	400	550		45	66	127
Mean max. root length (m)	3.5	4.2	9.1		1.5	3.0	3.6
Maximum root length (m)	4.7	6.4	10.4		1.9	4.5	6.1
Mean max. root depth (m)	1.8	2.4	2.9		1.3	1.6	1.3
Maximum root depth (m)	2.1	2.6	3.1		2.2	2.1	1.5

DBH = Diameter at Breast Height (height measured to 1.4 m on uphill side of tree).

Radiata pine: Details of the root morphology of the three age classes of radiata pine (Watson & O'Loughlin 1990), are summarised below.

For the three age classes (Table 1) the lateral roots of the majority of trees were distributed asymmetrically around the stump. The 8-year roots grew predominantly across and up slope, whereas the older root systems showed a growth preference for across and down slope. Generally, in all classes the longer roots grew within 0.1 m of the ground surface. The mean maximums and maximum root lengths are given in Table 1. All lateral roots of the younger trees were found in the upper 0.5 m of the soil profile. In the 16 and 25-year trees, lateral root growth was restricted to the top 1 m of soil, with 75% confined to less than 0.5 m from the surface. All major branching of the 8 year lateral roots occurred within 0.5 m of the stump. For the 16 and 25 year root systems all the major branching had taken place within 1.5 m and 2.0 m of the stump respectively. Approximately 95%, 85%, and 80% of the mass of the 8, 16 and 25-year root systems, respectively, were within 1 m of the stump.

There was strong vertical root growth in the two younger age groups. The 25-year vertical root growth was restricted at about 2.6 m by layers of saturated clay. The mean maximums and maximum root depths are given in Table 1. At all ages there was strong root development directly below the stump. At age 16 this were supplemented by sinker roots which grew from the underside of the main laterals, up to 2 m out from the stump and penetrated to depths of 1.8 m. By age 25, sinker roots were growing up to 3 m from the stump and to a size and depth (approximately 3 m) similar to those roots growing from underneath the stump. Approximately 85, 80 and 75% of the mass of the 8, 16 and 25 year root systems, respectively, were within 1 m of the soil surface.

Root Biomass

Biomass studies have been traditionally been carried out to determine the productivity and growth rates of tree species. Usually in these studies a complete tree is removed and partitioned in various above and below ground components. From these components various parameters can be measured (Bohm 1979) and relationships derived, such that parameters, which are difficult or time consuming to obtain, can be estimated from more readily available datasets.

On average, radiata pine root boles contained 40% of the total root biomass at age 8, and over the next 8 years increased to 50%, then remained reasonably constant (Table 2). The percentage biomass of the kanuka root boles remained constant at about 40% from ages 6 through to 32 years (Table 3).

Table 2. Mean root biomass (kg) of radiata pine. Figures in parentheses represent mean percentages of totals, (from Watson & O'Loughlin 1990).

Root diameter class	Mean age, 8 yr	Mean age, 16 yr	Mean age, 25 yr
2 - 10 mm	1.8 (5)	8.7 (3)	14.8 (3)
10 - 20 mm	2.3 (6)	8.7 (3)	18.1 (4)
20 - 50 mm	7.3 (19)	33.8 (13)	95.5 (17)
50 - 100 mm	7.8 (21)	36.0 (14)	75.7 (12)
>100 mm	3.7 (10)	46.0 (17)	96.2 (17)
Root bole	14.5 (39)	132.8 (50)	259.4 (47)
Mean Totals	37.4	266.0	559.7

Table 3. Mean root biomass (kg) of Kanuka. Figures in parentheses represent mean percentages of totals.

Root diameter class	Mean age, 6 yr	Mean age, 16 yr	Mean age, 32 yr
2 - 10 mm	0.23 (28)	0.67 (29)	2.78 (14)
10 - 20 mm	0.11 (13)	0.28 (12)	2.31 (12)
20 - 50 mm	0.12 (14)	0.42 (19)	2.10 (10)
50 - 100 mm	0.02 (3)	0.06 (3)	2.07 (10)
>100 mm	-	-	3.09 (15)
Root bole	0.35 (42)	0.83 (37)	7.74 (39)
Mean totals	0.83	2.26	20.10

The total root biomass of the three radiata pine age classes was 9, 67, and 151 tonnes/ha (Table 4). The root biomass was increasing at a rate of 1-2 tonnes/ha /yr at age 8, 7-8 tonnes /ha/yr by 16 years and reaching 9-10 tonnes/ha/yr at year 25 (Watson & O'Loughlin 1990). For kanuka, root production stayed close to 2 tonnes/ha/yr for the first 16 years, increasing slightly to 3 tonne/ha /yr over the next 16 years.

The annual rate of root production of kanuka exceeds that of radiata pine for the first 9 years of growth (Fig 2). Though individually, kanuka root systems are smaller than radiata pine, the difference in biomass is more than compensated for by the higher kanuka stand densities. The increase in radiata pine root production is indicative of a developing canopy. The low stand densities of radiata pine would assure ample space for crown development. Uniform canopy heights are a feature of kanuka stands and indicate short period establishment. Very high stocking rates during establishment give rise to kanuka's initial high rate of root production. But as the stands age, progressive self-thinning increases as competition inhibits individual tree development. Therefore as the biomass of kanuka increases with age there is a corresponding decrease in stand density, hence a more or less static annual rate of root production after age 6.

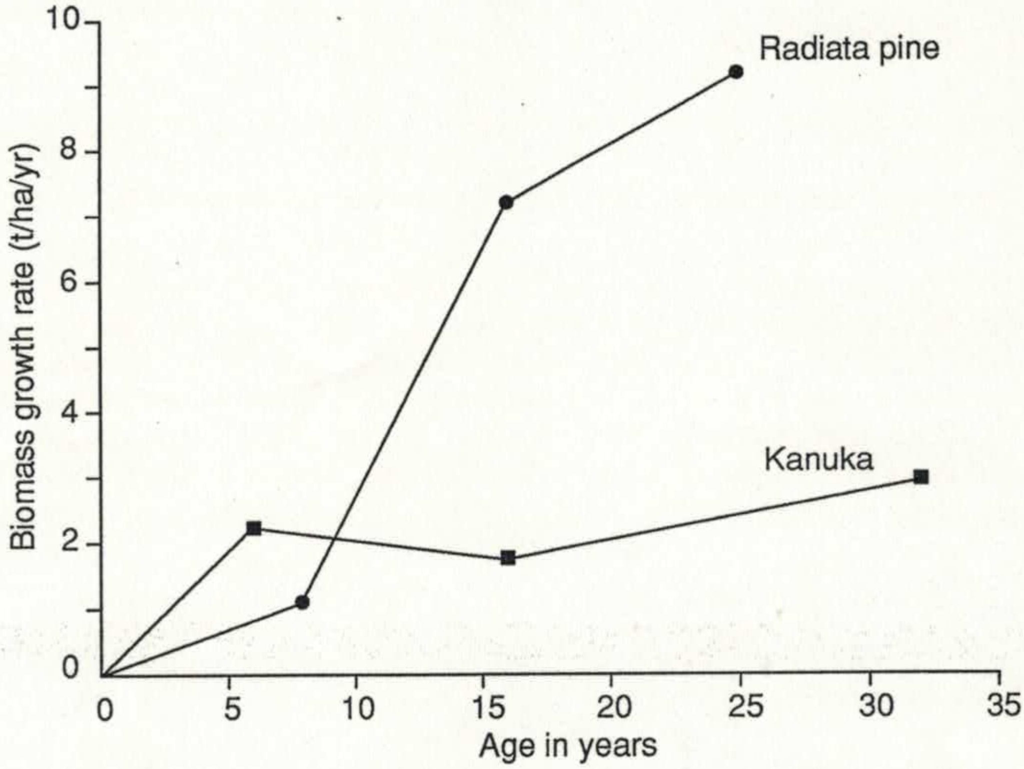

Fig. 2 A comparison in relationship between tree age (years) and annual rate of increase in biomass (t/ha/yr) between radiata pine and kanuka.

The radiata pine stand densities given in Table 4 represent final stocking rates. Currently, the initial planting densities of the three stands would have been in the order of 1250 stems/ha, thinned to 800 and 400 stems/ha at ages 5 and 9, respectively. During the first 8 years radiata pine would have had a lateral root growth rate of 0.43 m/yr (Table 1), and site occupancy, would have been obtained by the lateral roots in 3.7 years. Similarly, for kanuka, where the initial lateral root growth rate was 0.25 m/yr, site occupancy was completed in 1.8 yr. Rates of vertical root development of both radiata pine and kanuka, at least for the first 6 years, were 0.23 and 0.22m/yr, respectively.

Table 4. Stand densities of sampled trees and associated biomass parameters.

	Radiata pine				Kanuka		
Mean age (yrs)	8	16	25		6	16	32
Stand densities (stems/ha)	236	253	270		15870	12800	3900
Biomass (t/ha)	9	67	151		13	29	78
Biomass growth rate (t/ha/yr)	1.1	7.3	9.3		2.2	1.8	3.1

If the probability of an extreme flood on the Waipaoa River is used to indicate a storm likely to cause slope instability, the probability curve in Figure 3 suggests that there is a 29% chance of at least one extreme event every year (observed data suggests 25%) and a 100% chance every 10 years. Erosion susceptible slopes planted in radiata pine acquire full root occupancy in approximately 4 years, a period during which there is a 75% chance of experiencing a severe storm. In contrast, similar slopes growing kanuka, which reach root occupancy in approximately 2 years, have a 50% probability of experiencing a significant event during that time.

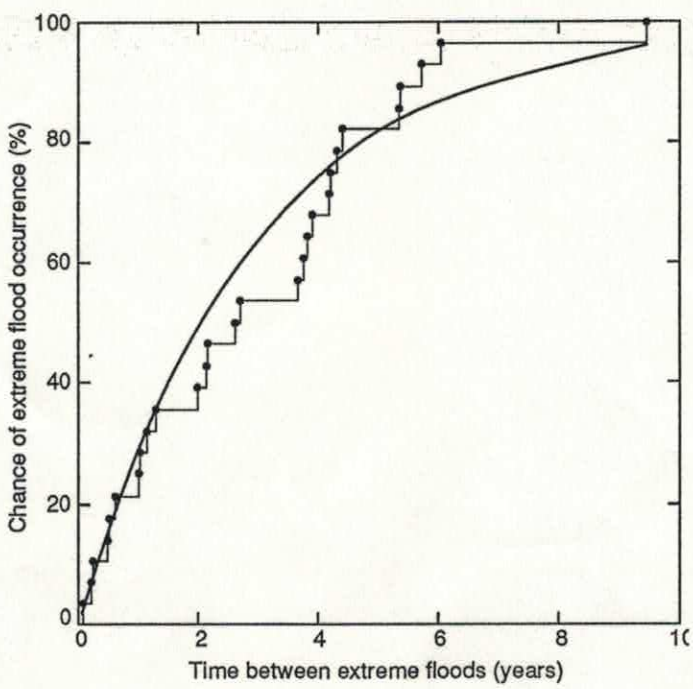

Fig. 3 The relationship of time (years) between extreme floods of the Waipaoa River at Kanakanaia (Discharge >1500 m^3/sec.) and the chance of their occurrence. Analysis is based on time intervals between twenty-nine 20th century floods. The step function represents observations, the curve gives expected chance of occurrence, (Kelliher *et al.* 1994).

Previous research has shown that during high intensity tropical cyclones, trees less than 6 years growing on erosion susceptible slopes were no better in preventing shallow (less than 1.5 m deep) translational landslides, than similar slopes in pasture (Marden *et al.* 1991). The initial slow, vertical root growth rates shown by both tree species may account in part for this observation.

Root Strength and Rates of Decay

Most studies of live root strength and rates of loss of root strength with decay have measured tensile strength of individual tree roots, collected from live trees or stumps of trees of known cutting date. To preserve root-moisture content prior to testing, root samples are sealed in plastic bags and if necessary kept in cool storage. During analysis either ends of the root are clamped into a testing device and a known force applied. The resistance to being pulled apart is taken as the measure of the tensile strength of the root. The methods and techniques of sample collection and testing are described in O'Loughlin & Watson (1979).

In forest soils in comparable climatic regions, the rate of decay of root-wood of different tree species appear to be remarkably similar. This is shown in Table 5, which gives data from New Zealand (O'Loughlin & Watson 1979,1981), USA, and Canada (O'Loughlin & Ziemer 1982; Burroughs & Thomas 1977; Ziemer & Swanston 1977).

Table 5. Rate of loss of root-wood tensile strength for roots < 15 mm diameter.

Tree species	Country of origin	Time to lose 50% of tensile strength (yrs)	Loss of Tensile Strength (MPa/yr)
Rata (*Metrosideros* spp.)	New Zealand	4.1	5.4
Beech (*Nothofagus* spp.)	New Zealand	2.8	5.5
Radiata pine (*Pinus radiata*)	New Zealand	1.2	5.9
Douglas fir (*Pseudotsuga menziesii*)	Oregon, USA	1.0	6.2
Western hemlock (*Tsuga heterphylla*)	BC, Canada	4.0	5.5
Sitka spruce (*Picea sitchensis*)	Alaska, USA	2.0	4.8

Information on manuka (*Leptospermum scoparium*) and kanuka stem-wood durability (Forest Research Institute 1982) suggests that the properties of their root-wood are similar. Although the tensile strength of live kanuka roots have yet to be determined, live mean tensile strength of manuka was found to be 34.2 MPa (Watson & O'Loughlin 1985), similar to the live mean root-wood tensile strength of *Nothofagus* spp., 32.5 MPa (O'Loughlin & Watson 1981). If the rates of decay of root-wood are similar, then the rates of loss of tensile strength for kanuka and *Nothofagus* spp. will be comparable. Therefore kanuka root-wood could be expected to lose half its tensile strength in 2.8 years after felling, and be in an advanced state of decay by about 5 years.

The mean tensile strength of live radiata pine was 17.6 MPa. After logging the root systems loose half their tensile strength within 1.2 years, and at 3 years, roots > 50 mm diameter show signs of advanced deterioration (O'Loughlin & Watson 1979).

If kanuka was to be felled and replaced by another tree species, the tensile strength of decaying kanuka root systems would after about 4 years be minimal. Trees require between 6 to 8 years before contributing to slope stability (Marden *et al.* 1991) . Therefore there is a period of approximately 3 years that the slopes would be left without an effective tree cover, and from Figure 3, a 3-year period would represent a 63% chance of a major storm event. Similarly, if radiata pine was to be replaced, the tensile strength of the original trees would be at a minimum within 2 years after felling, leaving a period of vulnerability of about 5 years, and an 82% chance of a major storm event.

In summary, live kanuka root-wood is approximately twice the tensile strength of that of radiata pine, and after felling would take twice as long to lose its soil reinforcement abilities. Although the difference in time that either species would leave a slope vulnerable to a major storm is only 2 years, the increase in probability of such an event happening is in the order of 20%.

CONCLUSIONS

In the initial years, kanuka would be the more favoured tree species. Kanuka has a greater initial lateral root growth rate, and by virtue of its higher stocking rates root systems attain full site occupancy in about 2 years after establishment, half that of radiata pine. After 8-10 years rates of increase of root biomass and root length for radiata pine are greater than that of kanuka, and continue to be for at least the age of the trees considered in this study.

It may not be strictly valid to directly compare the root systems of managed commercially grown stands of trees to that of naturally seeded ones. Physiological differences of the species aside, one of the main factors when considering trees and slope stability, is the number of trees per unit area of land. Because of the commercial requirement of high quality saw logs there is an increasing trend towards lower stand densities and hence an increase in storm vulnerability. If in unstable areas, tree species such as radiata pine are needed to fill the dual roles of commercial forestry and slope stability, then an increase in stocking rates, particularly for the first 8-10 years of establishment and a 3-5 year delay in thinning regimes, would allow, without too much compromise, fulfilment of both objectives.

Future work will be directed to more detailed laboratory and field studies aimed at investigating how soil shear strengths and root/soil cohesion are modified as soils approach saturation. If this can be accomplished for a range of topographies, soils and tree species, a calibrated model could be developed that would enable a better understanding of the relationship between tree species and slope stability.

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