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Root development and whole-tree allometry of juvenile trees of five seed lots of *Pinus radiata* D.Don: implications for forest establishment on erosion-prone terrain, East Coast region, North Island, New Zealand

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Abstract

Background: Establishment of exotic forest on erosion-prone pastoral hill country in the East Coast region of New Zealand escalated following a major cyclonic storm in 1988. *Pinus radiata* D.Don is the predominant species used for erosion control. It has been suggested that planting densities could be reduced if faster growing *P. radiata* seedlings and cuttings from genetically improved seed lots were used.

Methods: A field-based trial was established to measure and compare annual growth rates between *P. radiata* seed lots (GF 16 and GF 19 seedlings and cuttings grown from GF 23 seed) used during the period of early forest establishment (1960s onwards) in this region and genetically improved seed lots (GF 27 seedlings and GF 28 cuttings) developed at a later date. Over a 4-year period, the above-ground parameters (diameter at breast height, root collar diameter, tree height and canopy diameter) were measured before whole trees (canopy and root systems) were destructively sampled.

Results: Root collar diameter (over bark) was most highly correlated with tree height, with r^2 ranging between 0.95 and 0.98 for all the seed lots, and all regressions were highly significant ($P < 0.001$). In any year of the trial, there were no differences among seed lots with respect to root collar diameter, total above-ground biomass or total below-ground biomass. By year 4, mean below-ground biomass comprised 17% of total biomass. There was no consistently significant difference among seed lots in the distribution of total below-ground biomass or root length with distance from the root bole, relative to depth, or in either their maximum lateral root spread or maximum root depth until year 4 when GF16S and GF27S had a greater ($P = 0.05$) maximum root spread than GF28C while the latter had developed a significantly greater ($P = 0.05$) proportion of its root biomass and root length within the top 0.5 m of the soil profile. The root cross-sectional area of vertical roots increased significantly with age but decreased with depth. Root orientation formed a 'bilateral fan-shaped' architecture.

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Conclusions: The absence of consistently significant differences among seed lots suggests that during the early 4 year post-establishment period, no one seed lot would provide earlier soil reinforcement or result in a superior level of slope stability than would any of the other seed lots trialled. Thus, irrespective of seed lot preferences, any reduction in the current recommended planting density for erosion-prone hill country would further increase the period of vulnerability and risk of young plantings to damage by storm-initiated landslides.

Keywords: Root development, Whole-tree biomass, Five seed lots, *P. radiata*, Erosion remediation

Background

Shallow landslides (soil slips) occur mostly as a result of storms and are the main erosion process of concern (Crozier 2005). Such landslides have resulted in significant soil loss from extensively grazed, steep, erosion-prone pastoral hill country over the past five decades and have been most widespread in regions where the geology consists of young, late Tertiary-aged sedimentary bedrock (Mazengarb and Speden 2000). The East Coast of the North Island is one such region that is widely recognised as being vulnerable to slope failure during major storm events. Since the early 1960s, *Pinus radiata* D.Don has been the predominant species used to reforest extensive areas (~163,000 ha; from Phillips et al. 2013) of the most severely affected class 8 pastoral hill country (National Water and Soil Conservation Organisation [NWASCO] 1975) to limit further erosion and further reforestation is planned. Our current understanding of the effectiveness of *P. radiata* in reducing the incidence of storm-initiated shallow landslides is largely based on studies initiated in the East Coast region following Cyclone Bola (1988) (Marden et al. 1991; Phillips et al. 1991; Marden and Rowan 1993; Phillips and Marden 2005; Hancox and Wright. 2005). In general terms, the below-ground components (roots) provide mechanical reinforcement (Watson et al. 1999) and are the means by which trees extract soil moisture from the soil to reduce pore water pressures (Ekanayake et al. 1997) while the above-ground components of vegetation (canopy) reduce the ability of rainfall to cause shallow landsliding through the processes of interception (Kelliher et al. 1992) and transpiration (Pearce et al. 1987). These processes become most effective when full root occupancy (lateral roots of adjacent trees overlap) and canopy closure (canopies of individual trees touch) first occurs, and they improve with increasing tree age and/or planting density (Kelliher, F. M., Marden, M., & Watson, A. J.: Stability of land and tree planting density East Coast, North Island, unpublished)[1]. This was aptly demonstrated by Marden and Rowan (1993) who noted that where hill slopes planted in pines had attained canopy closure before Cyclone Bola, they were considerably less prone to rainfall-induced landslides than were either pastured hill sides or young stands of pine where canopy closure had yet to occur. On further investigation, they found that young forest stands <6 years old and pastured hill slopes at the time of Cyclone Bola sustained similar levels of landslide damage and up to 16 times greater than for either exotic plantings or indigenous forest where the canopy was fully closed. This relationship was particularly strong for hill country underlain by Tertiary-aged sedimentary bedrock where landslides are typically shallow and translational (Marden et al. 1991). A similar result was found in an area of the Coromandel region of New Zealand that was affected by a severe storm in March 1995 with few slope failures occurring within closed-canopy exotic forest (Marden and Rowan 2015). These results suggests that the level of landslide damage likely to occur within a forest stand is dependant, at least in part, on the age, density and maturity of the trees at the time of a major storm and that during such an event, there is little difference in the magnitude of interception loss across different closed-canopy vegetation communities as a percentage of rainfall (Rowe et al. 1999).

Extensive areas of pastoral hill country in the East Cape were sold to forestry interests in the mid to late 1990s because of the severity and extent of landslide damage sustained during Cyclone Bola. Coincident with this period of increased land use conversion to exotic forest, there was a perception, based largely on anecdotal evidence, that seedlings derived from genetically improved seed lots and physiologically aged cuttings were sturdier and developed faster than those grown from earlier seed lots. Furthermore, it was presumed that the faster growth of plants from genetically improved seed lots would lead to earlier mechanical (root) reinforcement of the root systems and an earlier closing of the canopy to those grown from seed lots available at the time of early forest establishment in this region. This presumption led to the idea that the current planting density requirements for erosion-prone hill country in this region could be reduced. However, for newly forested areas, factors including planting density, mortality and growth rates (of both the above- and below-ground components of trees) are important in determining the length of the period (years) of vulnerability of planted stands to the initiation of shallow landslides, particularly during their formative years. Thus, (Kelliher, F. M., Marden, M., & Watson, A. J.:

Stability of land and tree planting density East Coast, North Island, unpublished)[1] stated 'Forest age and corresponding root and tree canopy development have a considerable influence on the risk and magnitude of damage caused by storm-induced landslides…' and 'Consideration of improved strains of *P. radiata* in formulating tree planting policy should not be done until comparative regional data on tree growth (i.e. root and canopy development to site-occupancy) are obtained…'.

At that time, the recommended planting density for the steepest of the eroding land classes was 1250 stems ha^{-1} (Ministry of Forestry 1994). This recommendation was based on root-growth (Watson and O'Loughlin 1990) and canopy-development data (Grace et al. 1987) used to generate a site-occupancy model. This model used time-series data of the diameter of root systems and canopies (crown) of *P. radiata* 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 met. Site occupancy of <1 indicated that open spaces remained between adjacent trees (Kelliher, F. M., Marden, M., & Watson, A. J.: Stability of land and tree planting density East Coast, North Island, unpublished)[1]. However, 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.

In recognition of the shortfall of a regional time-series database for different *P. radiata* seed lots used during the long history of forest establishment in this region, and particularly for trees in the ≤8-year age bracket, a trial was established at an East Coast field site. Comparative above- and below-ground growth performance data for seedlings and cuttings grown from five different seed lots of *P. radiata* was collected annually for a period of four successive years. The chosen site is representative of hill country with a high susceptibility to the initiation of shallow landslides and thus similar areas are destined for future afforestation.

Specifically, the aims of the current study were to: (i) provide field-based, root-related data and allometric relationships for each of five different seed lots of *P. radiata* as inputs for slope stability and/or soil reinforcement modelling, many of which suffer from a paucity of the types of data collected in this study, particularly for juvenile (≤8 years old) trees; (ii) establish whether or not there were significant differences in the growth rate among seedlings and cuttings grown from seed lots available at the time of early forest establishment in this region (1960s onwards), and planting stock (both seedlings and cuttings) grown from genetically improved seed lots available in more recent times; and then (iii) based on the findings, evaluate whether or not there is sufficient evidence in support of amending the current planting density recommendations for erosion-prone hill country likely to be afforested in the future.

Methods

Site

The site is located within Okiwa Forest (178° 04′, 38° 23′) approximately 20-km inland of Tolaga Bay in the East Coast region of the North Island, New Zealand (Fig. 1a).

The site is steep (42°), north facing (340°), is located on class 7 (National Water and Soil Conservation Organisation [NWASCO] 1975) land and occurs at an elevation of 450 m above sea level. The site index[2] for *P. radiata* is 30–35 (Hockey, M., & Page, M.: Internal New Zealand Forest Service Report, New Zealand Forest Service, unpublished)[3].

This area consists of deeply dissected hill country underlain by sedimentary bedrock comprising alternating sandstone and mudstone of late Tertiary age (Mazengarb and Speden 2000). Coverbed deposits consisting of volcanic ash and colluvium are deep (>1 m) and well preserved on localised gently sloping dip slopes but are shallow (<0.5 m) and skeletal on the predominant steeper slopes. Shallow translational landslides of the debris-slide/flow-avalanche types with a measured mean depth of 0.96 m predominate (Marden et al. 1991). Formerly in pasture, this area sustained severe landslide damage during Cyclone Bola in March 1988. Soils are well drained Typic Orthic Recent Soil typically associated with land that has been eroded or has received sediment as a result of slope processes (Hewitt 2010). They correlate with the Inceptisols of Soil Taxonomy (Soil Survey Staff 1992). A soil profile typical of class 7 hill country is shown in Table 1.

Climate

The climate of the East Coast region is warm temperate maritime, with moist summers and cool wet winters. Mean annual rainfall varies from about 700 mm at the coast to 2500 mm at higher elevations (New Zealand Meteorological Service 1973). Lengthy periods of little or no rainfall are common during January to April (midsummer to late autumn). This region has a history of extreme rainfall events that have been a major feature contributing to the unstable nature of steep hill country. Storms may be of tropical origin (e.g. Cyclone Bola in 1988) or from more localised weather patterns.

Plant material

Seedlings were raised from seed lots GF 16, GF 19 and GF 27, and cuttings of GF 23 (physiologically 4 years old) and GF 28 plants (physiologically 1 year old) were grown from plant material cut from stools (parent plants). Both seedlings and cuttings were grown at

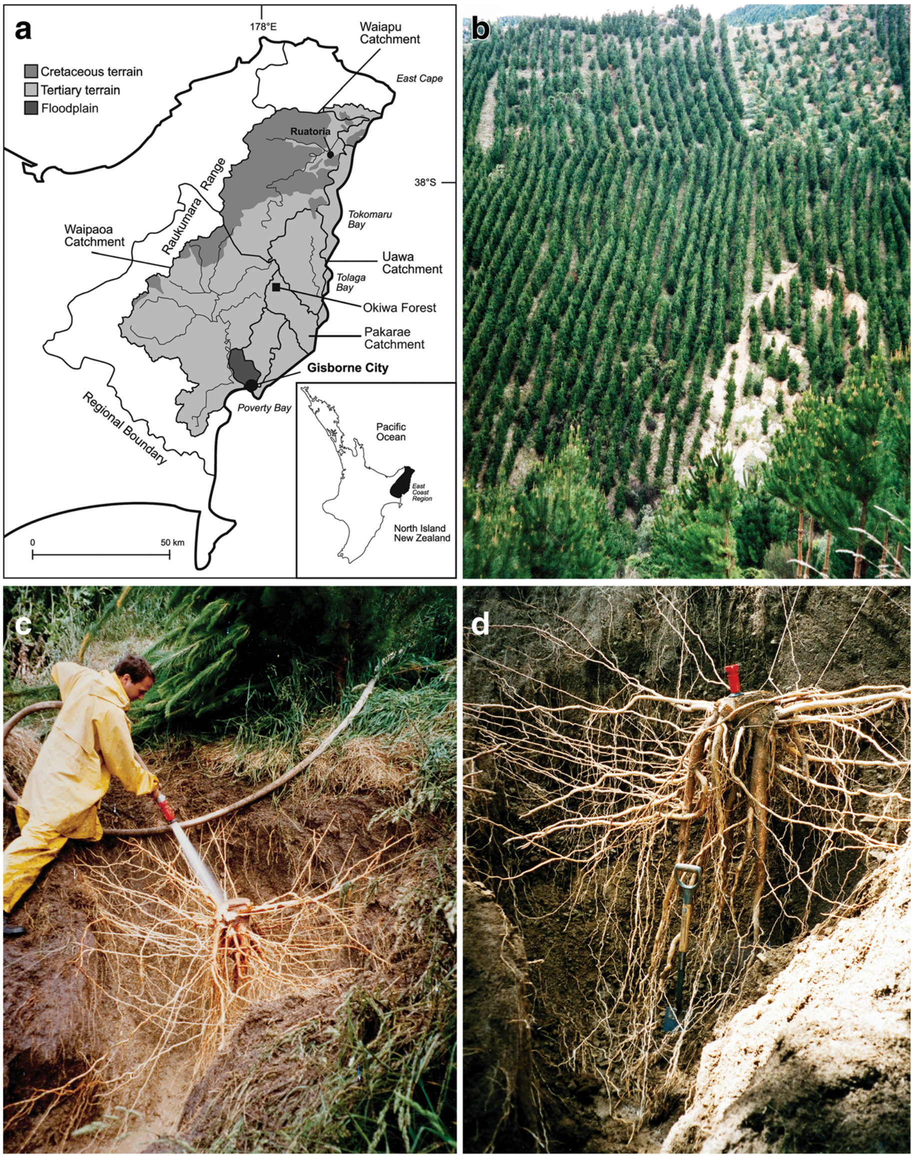

Fig. 1 Location (**a**) and oblique view (**b**) of Okiwa trial site, sluicing root system (**c**), in situ root system (**d**) of 4-year-old *Pinus radiata*

Table 1 Soil profile at Okiwa trial site

Horizon	Depth	Profile description
Ap	0–16 cm	Dark brown (10 YR 3/3), very slightly gravelly fine sandy loam, non-sticky, very weak soil strength, earthy pedality, many fine polyhedral peds, gravels of strongly weathered sandstone gravels to 5-cm diameter, many extremely fine roots, distinct wavy boundary
Bw	16–28 cm	Yellowish brown (10 YR 5/4), moderately gravelly fine sandy loam, non-sticky, very weak soil strength, friable failure, earthy pedality, many fine polyhedral peds, moderately weathered sandstone gravels to 5-cm diameter, common extremely fine roots, indistinct wavy boundary
BC	28–56 cm	Light olive brown (2.5 YR 5/4), very gravelly fine sandy loam, non-sticky, very weak soil strength, friable failure, earthy pedality, moderately weathered subangular gravels to 5 cm diameter, diffuse boundary
C	56+ cm	As above, but extremely gravelly, well drained

Puha Nursery (a New Zealand Forest Service nursery located in the East Coast region and specialising in raising *P. radiata*) using seed that was sourced from reputable suppliers and grown using standard nursery practices. Specific seed lots are referred to using the GF number (based on measurements of growth and form of known parent trees) with either the suffix 'S' to denote a seedling or 'C' to indicate a cutting; otherwise, the generalised terms 'seed lot' or 'plant material type' are used. These particular seed lots were chosen because they have been planted extensively throughout the East Coast region since exotic forest establishment began in the early 1960s and because at the time of trial establishment, seedlings grown from seed lot GF 16 and GF 19 and cuttings from seed lot GF 23 stools were the earliest available, while GF 27 seedlings and cuttings grown from seed lot GF 28 stools were the latest available material.

Trial design

A randomised block design was used to account for variations in site conditions between the top and bottom of the trial site (e.g. wind, soil depth). Six hundred bare-rooted *P. radiata* seedlings and cuttings were labelled by GF type and planted in three rectangular blocks with equal numbers of each seed lot planted in each block (Additional file 1, Fig. 1b). Each block consisted of 10 rows spaced 2 m apart and oriented across-slope, that is, parallel to the contours, and 20 columns at 4-m spacing each extending 60 m downslope from the top of a ridge to give a stand density of 1250 stems ha^{-1} as recommended for class 7 erosion-prone hill country targeted for reforestation (Ministry of Forestry 1994). The trial was established at around the same time as the surrounding plantings, thereby minimising potential edge effects. The authors were present during planting to ensure correct plant placement, as per the block design. Shortly after establishment, seedlings and cuttings were release sprayed using Velpar (DuPont; active ingredient hexazinone 250 g L^{-1}) at a rate of 4 L ha^{-1}. Trees were not pruned or thinned during the course of the trial. An annual site inspection was carried out to note which trees had died, toppled, suffered stem snap or were not successfully released. Dead, missing and damaged trees were eliminated from the database before using the computer-generated RANUNI sampling system in SAS (version 6) (SAS Institute Inc., Cary, NC, USA) to select trees for excavation. Tree gaps were not replanted.

Data collection

Ten seedlings of each seed lot (i.e. 50 trees at year 0) were partitioned in order to measure the incremental increase in growth performance between nursery-produced planting materials and seedlings after 1 year in the ground. A further 10 sample trees of each of the five seed lots were excavated and destructively partitioned in years 1 and 2 (i.e. 50 trees per year). However, only five sample trees of each seed lot were excavated in year 3 (i.e. 25 trees), and only three sample trees of each of seed lots GF 16S, GF 27S and GF 28C were excavated in year 4 (i.e. 9 trees in total). Tree excavations planned for years 5 and 6 were abandoned.

Before removing trees from the field site tree height, RCD (root collar diameter over bark measured 0.1 m above-ground level) and DBH (diameter at breast height over bark at 1.4 m above-ground) were measured. The canopy diameter of individual trees was taken as the average of measurements in both the across-slope (i.e. along contour) and the upslope/downslope direction. Sample trees were then felled at ground level, and the above-ground component was removed off-site for partitioning into foliage, branch and stem and then dried and weighed. Excavation of the root systems and measurement methods followed well-established procedures (e.g. Watson et al. 1999). High-pressure water was used to remove the soil and expose the root systems to the extremity of the longest lateral root and the deepest vertical (tap and/or sinker) root (Fig. 1c). Once the root systems of sample trees excavated in years 3 and 4 were exposed, the maximum length of each of the lateral roots and the maximum root depth were measured in situ. In addition, the root cross-sectional area (CSA) data of individual vertical roots located both directly below the root bole (tap root) and sinker roots (developed from lateral roots) was measured where they crossed each incremental 0.5-m depth boundary. The root mass at each 0.5-m depth boundary was then calculated using πr^2 and was standardised across all excavated trees by dividing the root area by the area of soil (mm^2 m^{-2}) occupied. The latter was also determined using πr^2 and the radius of the longest root. Root CSA of the lateral roots was not measured. The diameter of the whole root system was recorded as the average of the longest lateral roots measured in two directions (across-slope and up-and-down-slope), and this was used to calculate temporal changes in root spread. Root orientation was determined in the field by measuring the total length (radius) of all lateral roots in 45° sectors oriented to the upslope direction. Roots oriented between 270° and 90° were considered to be in the upslope direction, and those oriented between 90° and 270° deemed to be oriented in the downslope direction. On completion of the in situ measurements and for future reference, each root system was photographed (Fig. 1d) and then removed from the field site. Whole root systems were washed to remove adhering mineral matter. Below-ground components were partitioned into root bole (stump) and roots. Root distribution (by mass and length), relative to the root bole, was obtained by systematically dissecting the root systems into 0.5-m radial and depth segments and then sorting by diameter size classes (<1 mm, fibrous, 1–2, 2.1–5.0, 5.1–10.0, 10.1–20.0 mm over bark) (Watson and O'Loughlin 1990). Root length (excluding fibrous roots) was measured by laying pieces of root end for end alongside a tape measure (Watson et al. 1999). A recovery efficiency of 90% was estimated for roots ≥1-mm diameter and 80% for roots <1-mm diameter (fibrous). All plant components, both above- and below-ground, were oven-dried at 100 °C until no further weight loss was detectable (24-h minimum) and then weighed to the nearest 0.1 g. Biomass and root-shoot ratios were calculated using dry mass.

Statistical analyses

Analysis of variance (ANOVA) was used to determine the effects of year and seed lot on above- and below-ground parameters. The Student-Newman-Keuls post hoc analysis was used to determine differences among the seed lots within a year and among years when all seed lots were averaged within each year. The normality of each analysis was determined by visual assessment of residual plots. The root biomass and root length data at 0.5-m depth and radial intervals exhibited non-normality due largely to the high prevalence of depth and radial segments in which no or little root material was recorded. The radial and depth segmented root biomass and length data was therefore transformed using the equation $\log_e(x + c)$, where x was the root biomass or root length and c was 1. Analysis of total root biomass and total root length with distance from the stem was conducted using three-factorial ANOVA with the factors distance, year and seed lot. Linear regression was used to fit RCD and tree height data. Root collar diameter (over bark) was used in the analysis of tree allometry instead of DBH because the trees did not reach DBH height (1.4 m) until year 2 of the trial. The relationship between RCD and below-ground biomass (BGB), total root biomass (>2- and >5-mm diameter) and total root length (>2- and >5-mm diameter) was analysed using two-parameter exponential growth analysis. The regression curves for total root length and RCD showed a separation between the two regressions but an unpaired, two tailed, t test of the slopes for the >2- and >5-mm root size classes showed no difference ($P = 0.178$) between the two size groupings, and this was also the case for root biomass ($P = 0.741$). Therefore, analysis of total root length and biomass with distance and depth from the stem was undertaken using total root length and biomass, respectively, for roots >2 mm. The slope of the regression is represented by b in the exponential growth equation ($y = a\exp^{bx}$).

Above-ground, plot-based measurements were recorded for 10 trees of each seed lot in both years 3 and 4. However, below-ground analysis was undertaken on a sub-sample of five trees of each seed lot in year 3 and three trees each of three seed lots in year 4. Two-sided, two sample (unpaired) t tests were used to test for significant differences in tree height, canopy diameter, RCD and DBH between the excavated trees of each seed lot and the plot trees that were measured but not excavated.

ANOVA analyses were conducted using Genstat 12 software (VSN International, Hempstead, UK) and were considered to be significant if $P < 0.05$. The Student-Newman-Keuls analyses were used to indicate pairwise differences at $P = 0.05$ and were also conducted using Genstat 12. All regression analyses were undertaken using SigmaPlot 12.5 software (Systat Software, San Jose, USA). All data are presented as non-transformed means with standard error unless otherwise stated.

Results and discussion

A survival rate of 85% for establishment in this region is considered acceptable by the forest industry, and the overall survival rate for the current trial was 87% over a 4-year period. The intention of this trial was to excavate 10 complete trees of each of the five seed lots annually over a period of six consecutive years for destructive partitioning into their above- and below-ground components. However, only 25 trees were excavated in year 3. Nine trees were excavated in year 4, and no excavations occurred in years 5 and 6 due to increasing work load and diminishing resources.

Comparative field-based data for juvenile *P. radiata* are rare and limited to previous studies by Watson and Tombleson (2002, 2004), Klomp and Hong (1985) and Phillips et al. (2015). In addition, this section focuses on those growth metrics most commonly used in the literature for modelling the contribution of tree roots (root occupancy) to soil reinforcement and slope stability in general, including canopy closure, where shallow landslides are the most common form of slope failure.

Allometric relationships

The Student-Newman-Keuls analysis for each year of the trial showed few differences among seed lots with respect to height (Additional file 2). In year 1, GF23C was significantly ($P = 0.05$) shorter than GF28C, but there were no further differences among any of the seed lots in year 2 or year 4. GF27S was shorter ($P = 0.05$) than GF16S in year 3, but the remaining seed lots were the same height as each other (Additional file 2). Similarly, a study by Klomp and Hong (1985) showed that there was no significant difference in height growth between cuttings and seedlings of *P. radiata* for the first 4 years after establishment, and this was also found to be the case for

3-year-old cuttings and seedlings in Watson and Tombleson's (2002) study. For all seed lots combined, the mean tree height at the Okiwa trial site increased from 1 m in year 1 to 6.9 m in year 4 with the mean tree height twice that of cuttings and seedlings of equivalent age from other field sites (Klomp and Hong 1985; Watson and Tombleson 2002).

There were no differences in RCD among the seed lots in years 1 and 2 of the trial. In year 3, RCD for GF23C and GF27S was similar but were significantly ($P = 0.05$) smaller than for the remaining seed lots. However, in year 4, there were few differences in RCD among seed lots, with the exception that for GF19S, the RCD was greater ($P = 0.05$) than for GF23C (Additional file 2). There was a strong linear relationship between RCD and tree height, with r^2 ranging between 0.95 and 0.98 for all of the seed lots, and all regressions were highly significant ($P < 0.001$; Fig. 2). Watson and Tombleson (2002) reported a significant difference in mean RCD between 3-year-old bare-root cuttings (70 mm), and both direct-sown seedlings (94 mm) and bare-root seedlings (88 mm). For equivalent-aged trees at Okiwa, mean RCD values for seedlings ranged from 102.2 to 134.6 mm and from 102.4 to 128.8 mm for cuttings (Additional file 2).

There were no differences among seed lots with respect to DBH in any year (Additional file 2). This was also the finding by Watson and Tombleson (2002). Comparisons of DBH for their 3-year-old plant types ranged from 70 to 94 mm, similar to that of seed lots at Okiwa (73 to 91 mm) (Additional file 2).

There were no differences among seed lots with respect to total above-ground biomass (AGB) (Additional file 2) or branch biomass (Additional file 3) in any year of the trial. There were also few differences among seed lots with respect to foliage and stem, with the exception that in year 4 of the trial, GF16S had more foliage ($P = 0.05$) than GF28C (Additional file 3) and in year 2, GF27S seedlings had more stem ($P = 0.05$) than

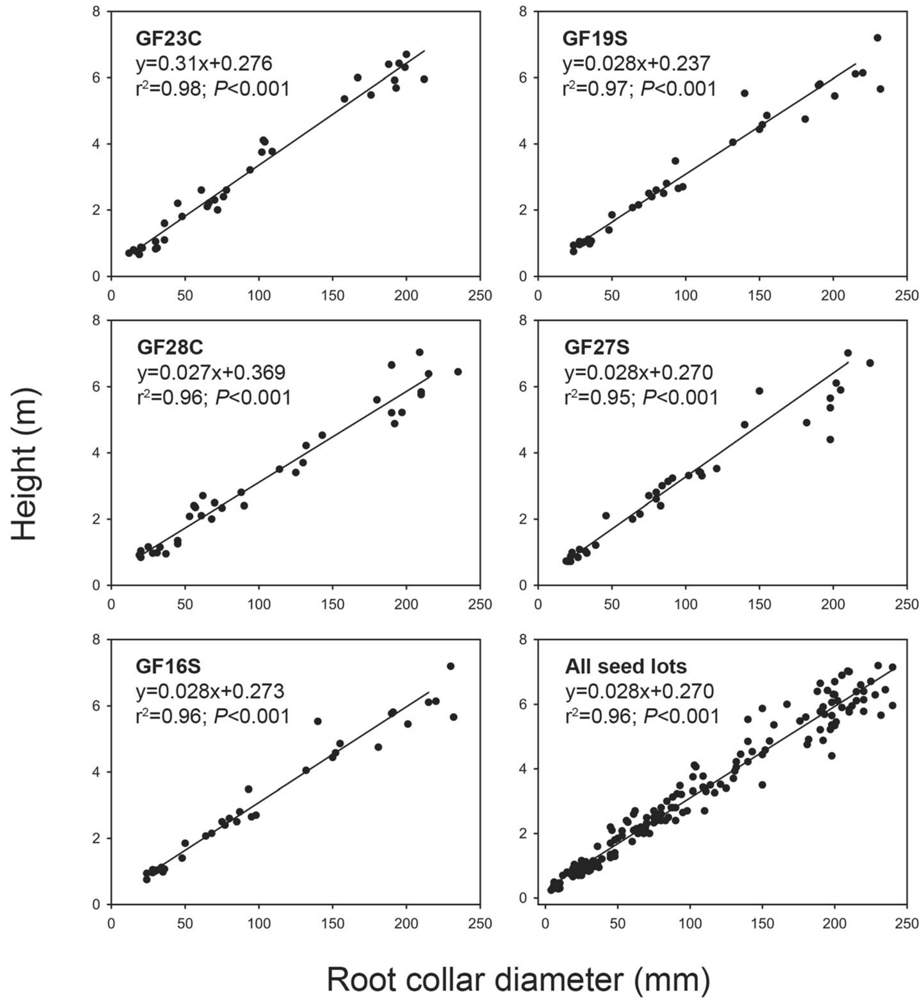

Fig. 2 Linear regression statistics and allometric relationships between RCD and tree height for individual and all seed lots combined

did GF23C seedlings. When all seed lots were combined, foliage, stem, branch and total AGB increased significantly in each year of the trial (Additional file 4) with the total AGB increasing from 226 g per seedling in year 1 to 45,936 g per tree in year 4 (Additional file 4).

In years 1, 2 and 4, there were no differences among seed lots with respect to below-ground biomass (BGB), but in year 3, GF27S trees had significantly less biomass than the other seed lots ($P = 0.05$) (Additional file 2). Mean BGB (all seed lots combined) increased significantly ($P = 0.05$) between each year of the trial (Additional file 4) from 49.3 g per seedling in year 1 to 9601.3 g per tree in year 4 (Additional file 4). Watson and Tombleson (2002) reported an indication of significant mean root bole biomass differences although there was no statistical evidence that the mean total below-ground biomass differed between plant material types. However, in our work, there were few differences in root bole biomass among any of the seed lots in any year of the trial except that GF28C trees had a greater ($P = 0.05$) average root bole biomass than did GF27S trees in year 3 (Additional file 3). Nonetheless, there was a significant increase in mean root bole biomass (all seed lots combined) with increasing age ($P = 0.005$) from 13.9 g in year 1 to 3621.8 g in year 4 (Additional file 4).

Two-parameter exponential regression analysis was a good fit for the RCD and BGB data, with r^2 ranging between 0.93 and 0.98, and all regressions were highly significant ($P < 0.001$; Fig. 3). Of the three seed lots for which data was collected in all 4 years, the slope of the lines were very similar, again reflecting little difference among seed lots with respect to BGB (Fig. 3).

In both years 3 and 4, two-sided, two sample (unpaired) *t* tests comparing tree height, canopy diameter, RCD and DBH among excavated trees of each seed lot with trees retained in the plot showed that RCD for excavated GF23C trees was less ($P = 0.002$) than that for the plot trees, while for the remainder of seed lots, there were no significant differences between the excavated and the plot trees in tree height, canopy diameter or

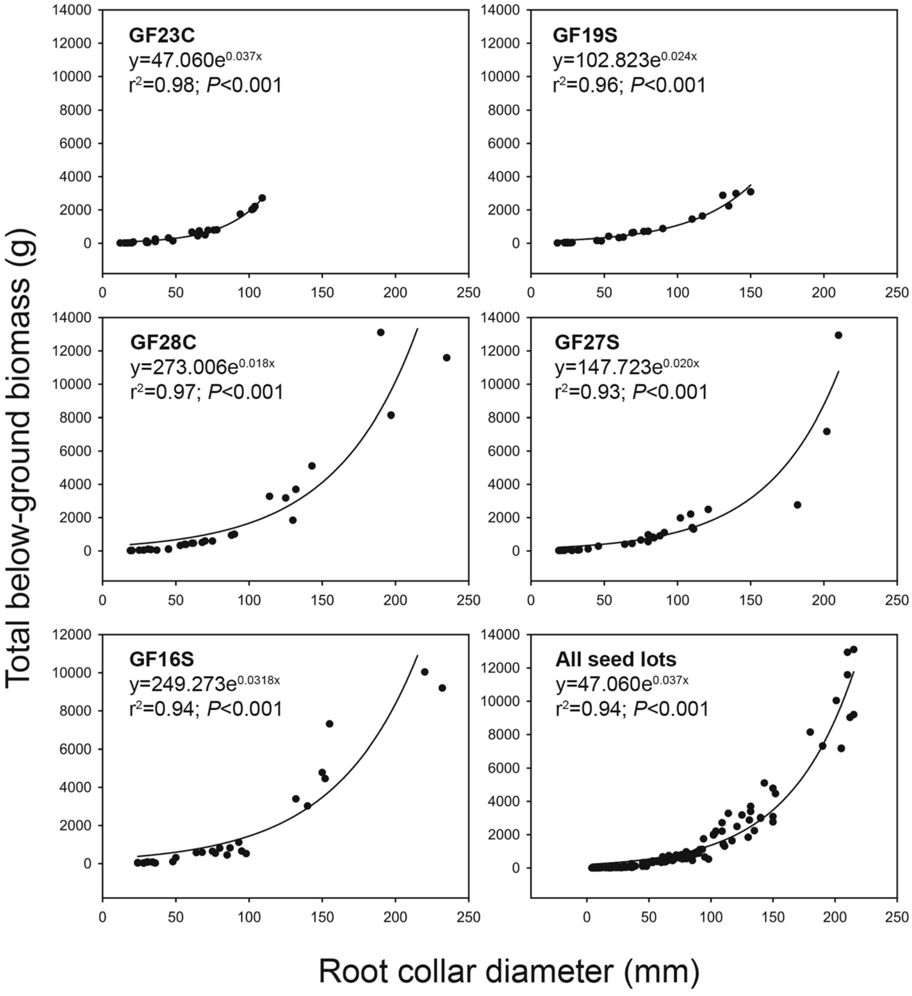

Fig. 3 Exponential growth and allometric relationships between RCD and total below-ground biomass for individual and all seed lots combined

DBH in either year. Overall, in both years 3 and 4, the above-ground metrics of the excavated trees provided a good representation of the growth performance of the plot trees.

Root biomass and biomass distribution

There was no difference in total root biomass (excluding root bole) among seed lots in any year of the trail (Additional file 3) There was a significant ($P = 0.05$) increase in mean root biomass in each year of the trial from 35.4 g in year 1 to 5979.5 g in year 4 when the seed lots were combined (Additional file 4). Exponential regression analysis of RCD and root biomass for roots >2- and >5-mm diameter size class showed very similar regressions for both root size classes (Fig. 4; Additional file 5). The regression analysis showed a strong relationship between RCD and root biomass, with RCD explaining between 87 and 97% of the variation in root biomass (Additional file 5).

In each year of the trial, the greatest amount of the root biomass ($P = 0.05$) was found in the 0–0.5-m depth increment (Fig. 5; Additional file 6), and there were no differences among seed lots for the first 3 years. However, by year 4, GF28C trees had significantly greater root biomass within the top 0.5 m of the soil profile than did the other seed lots (Fig. 5). For trees between 2 and 4 years old (all seed lots combined), ~96% of the below-ground biomass (inclusive of the root bole) occurs in the top 1 m of soil (from Additional file 6); thus, only ~4% occurs below the depth at which the majority of shallow landslides fail.

In each year of the trial, the greatest ($P = 0.05$) percentage of the root biomass occurred within a 0.5-m radius of the root bole, and for the first 2 years, this was the case for all the seed lots. However, by year 3, GF28C and GF16S had a greater proportion of their root biomass within this radius than did the remaining seed lots which were not different from each other (Fig. 6). Of the

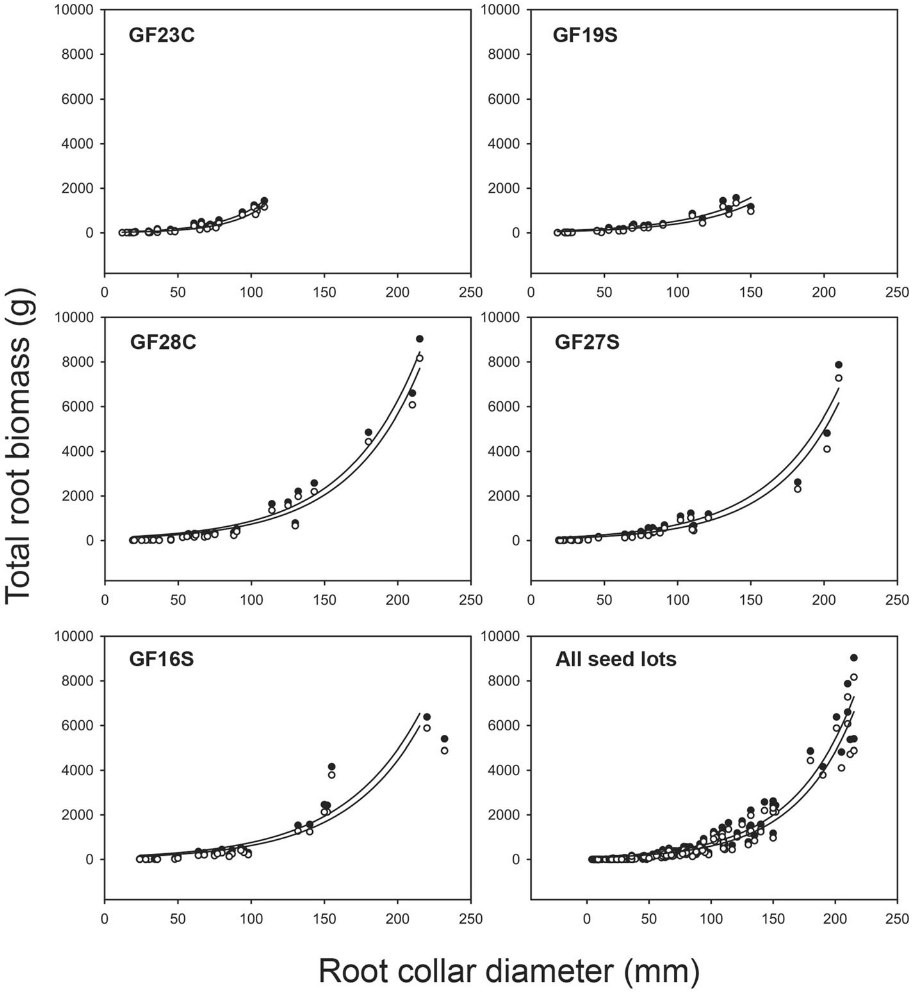

Fig. 4 Exponential growth and allometric relationships between RCD and total root biomass for >2-mm (*black circle*) and >5-mm (*white circle*) diameter for individual and all seed lots combined

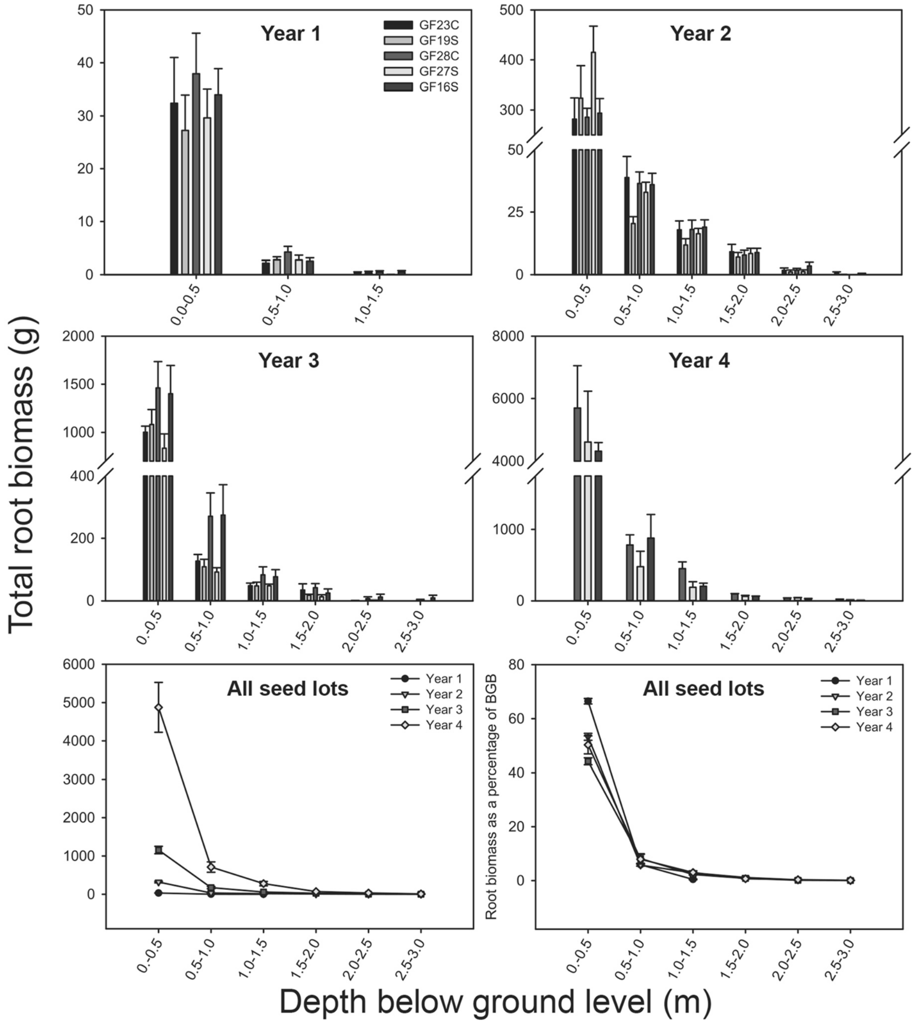

Fig. 5 Distribution of the total root biomass (g) of roots >2-mm diameter, for individual and all seed lots, in 0.5-m depth increments

three seed lots still monitored in year 4, GF28C had the greatest root biomass in the 0–0.5-m radius (Fig. 6). For all seed lots combined, 100% of the below-ground biomass (inclusive of root bole) of the 1-year-old seedlings and 92% of the mass of the 4-year-old trees were located within a 0.5-m radius of the root bole (from Additional file 7).

The high concentration of below-ground biomass within a 1-m radius of the root bole is likely a function of undercutting the tap root and trimming of the dominant lateral roots as part of normal nursery practice. At an early age, this results in the development of multiple vertical roots located directly below the root bole and of subsidiary sinker roots developed from lateral roots within a 1-m radius of the root bole (Fig. 1c, d).

Root biomass by root diameter size class

In 1-year-old plants (all seed lots combined), 58% of the total root biomass consisted of roots in the 2–5-mm diameter size class (Fig. 7), and by year 2, this had halved. The root biomass component of roots in the <2-mm diameter size class decreased with increasing age, and correspondingly, the root biomass in the >10-mm diameter size classes increased with increasing tree age. By year 4, the greatest proportion of total root biomass (38%) consisted of roots in the 20–50-mm diameter size class while roots in the <2-mm diameter size class contained the least (4%) of total root biomass (Fig. 7).

BGB/AGB ratio

There was no difference in this ratio among any of the seed lots in any year of the trial, remaining relatively constant at ~0.22 (Additional file 4). This is consistent with root/shoot biomass ratios (average approx. 20%) at a range of sites and stand ages in NZ and overseas (Watson and Tombleson 2002; Beets et al. 2007). While Watson and Tombleson (2002) did not provide a measure of the proportion of total BGB made up by the root

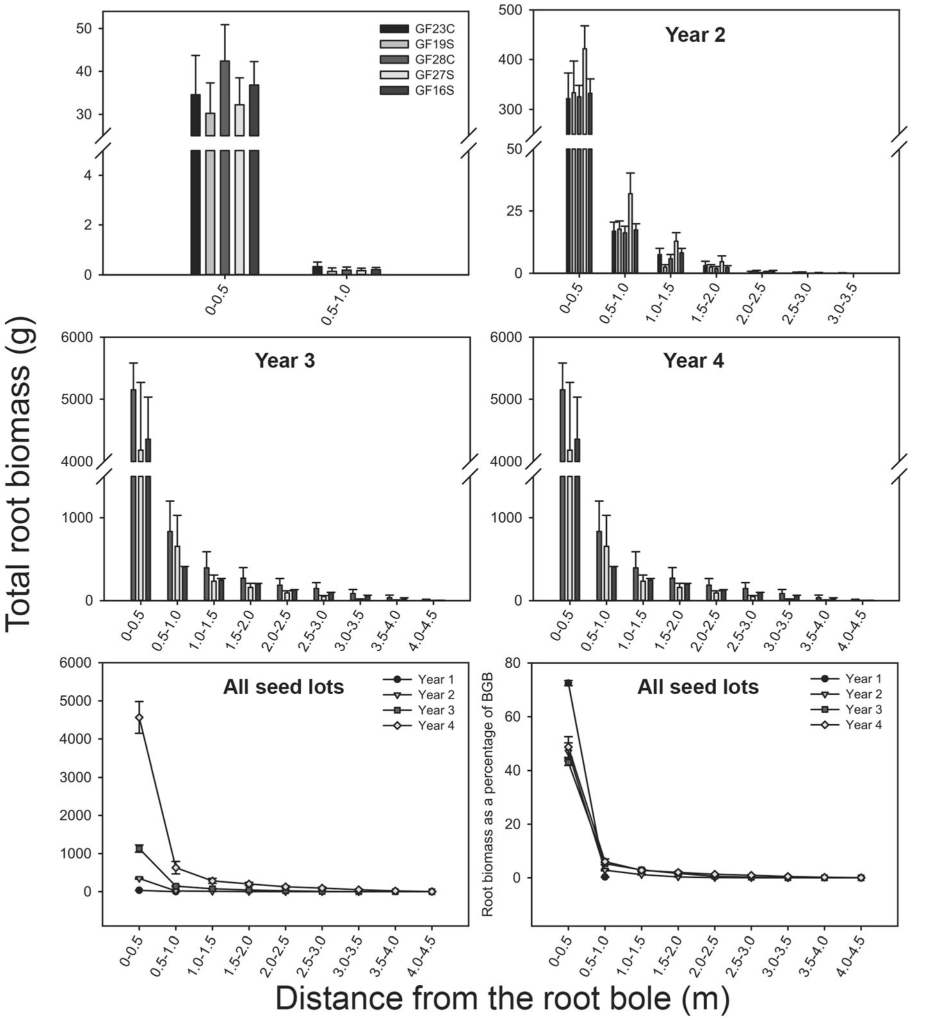

Fig. 6 Distribution of total biomass (g) of roots >2-mm diameter, for individual and all seed lots, in 0.5-m radial increments

bole, the results from the current study at Okiwa show that the root bole of 1-year-old trees contained ~29% of total BGB increasing to ~38% by year 4 (from Additional file 4).

There was no clear indication of a reduction in the BGB/AGB ratio with increasing age.

Root length and root system dimensions (diameter)

Two-parameter exponential growth analysis fitted the RCD and total root length data well with r^2 ranging between 0.69 and 0.89 for the >2-mm size class and between 0.73 and 0.89 for the >5-mm size class (Fig. 8, Additional file 5). For years 1 and 2, total root length was similar among seed lots and for all seed lots combined averaged 10.1 m in year 1 and 47.6 m in year 2. In year 3, GF16S had a greater ($P = 0.05$) root length than GF23C and GF27S, but was not different to GF19S and GF28C (data not shown), and for all seed lots combined averaged 95.5 m. This is more than double that reported for 3-year-old *P. radiata* (42.5 m) established at a trial site located on an alluvial terrace in Gisborne (Phillips et al. 2015) and considerably greater than the 15 m recorded by Watson and Tombleson (2002, 2004) from a trial located on a fertile farm site in Taranaki. In year 4, of the three remaining seed lots, GF28C had the greatest ($P = 0.05$) mean root length (236.7 m) while that of the other two seed lots was not different to each other (GF 28S = 198.5 m, GF 16S = 181.1 m). In each year of the trial, and for each of the seed lots, the greatest proportion of the total root length occurred within a 0.5-m radius of the stem (Fig. 9, $P = 0.05$; Additional file 8), in the top 0.5 m of the soil profile (Fig. 10, $P = 0.05$; Additional file 9), and decreased with increasing distance from the root bole and with increasing depth. For all seed lots combined, the mean total root length (all root size classes combined) for 1-year-old trees was 10.1 m increasing to 204 m by year 4 (Additional files 8 and 9).

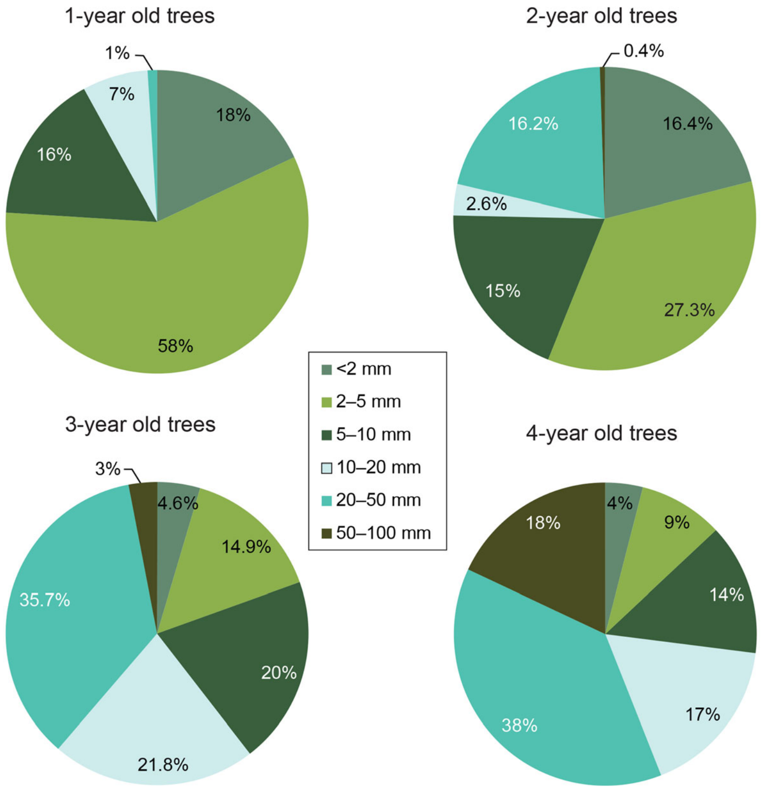

Fig. 7 Percent of total root biomass by root diameter (mm) for 1- to 4-year-old *P. radiata*, all seed lots combined

For each of the seed lots, the maximum extension of individual roots by year 4 was 4.5 m (Additional files 7 and 8). The mean maximum length (radius) of lateral roots (all seed lots combined) increased 10-fold from 0.29 m (SE = 0.01) in year 1 to 3.02 m (SE = 0.09) in year 4 (Additional file 10) to give a mean lateral root growth rate of ~0.75 m/year. By the second year, lateral roots of trees within rows (i.e. planted 2 m apart) had overlapped, and by the fourth year, the root systems of trees between rows (i.e. planted 4 m apart) had overlapped.

Maximum root spread did not differ among seed lots in the first 3 years, but in year 4, GF16S trees had a greater ($P = 0.041$) maximum root spread than did GF28C trees but was the same as trees from seed lot GF27S. The mean maximum root spread (diameter) for all seed lots increased significantly ($P = 0.05$) in each year of the trial reaching a maximum of 6.04 m in year 4 (SE = 0.18) (Additional file 10).

Root length by root size class

For all seed lots combined, roots in the 2–5-mm diameter size class made up the highest proportion of the total root length of 1- to 4-year-old trees. For 1-year-old trees, 96.1% of the total root length occurred within this diameter size class decreasing with increasing tree age to 62.5% of 4-year-old trees (Fig. 11).

Root depth

There were no differences in maximum rooting depth among seed lots ($P = 0.05$; Additional file 4) in any year. For all seed lots combined, the mean maximum root depth increased significantly between years from 0.96 m in year 1 (SE = 0.03) to 2.81 m (SE = 0.05) in year 4 (Additional file 10). Vertical *sinker* roots (roots developed from lateral roots at some distance from the root bole) descended to depths equal to that of the major vertical structural roots beneath the root bole. Based on data from all the sampled trees and, irrespective of seed lot, for the first 2 years, vertical roots developed at the rate of 1 m per year but averaged 0.6 m per year over the 4-year study period.

Watson and Tombleson (2002) reported a maximum root depth for 3-year-old trees of between 1.14 and 1.73 m with depth for the direct-sown seedlings being significantly greater than for that for either of the bare-rooted plant types. The mean maximum root depth of 3-year-old trees at Okiwa exceeded 2.5 m. Here, the colluvial soils, though stony, comprise loosely aggregated materials derived from earlier landslide failures, and as such contained no impediments to root development.

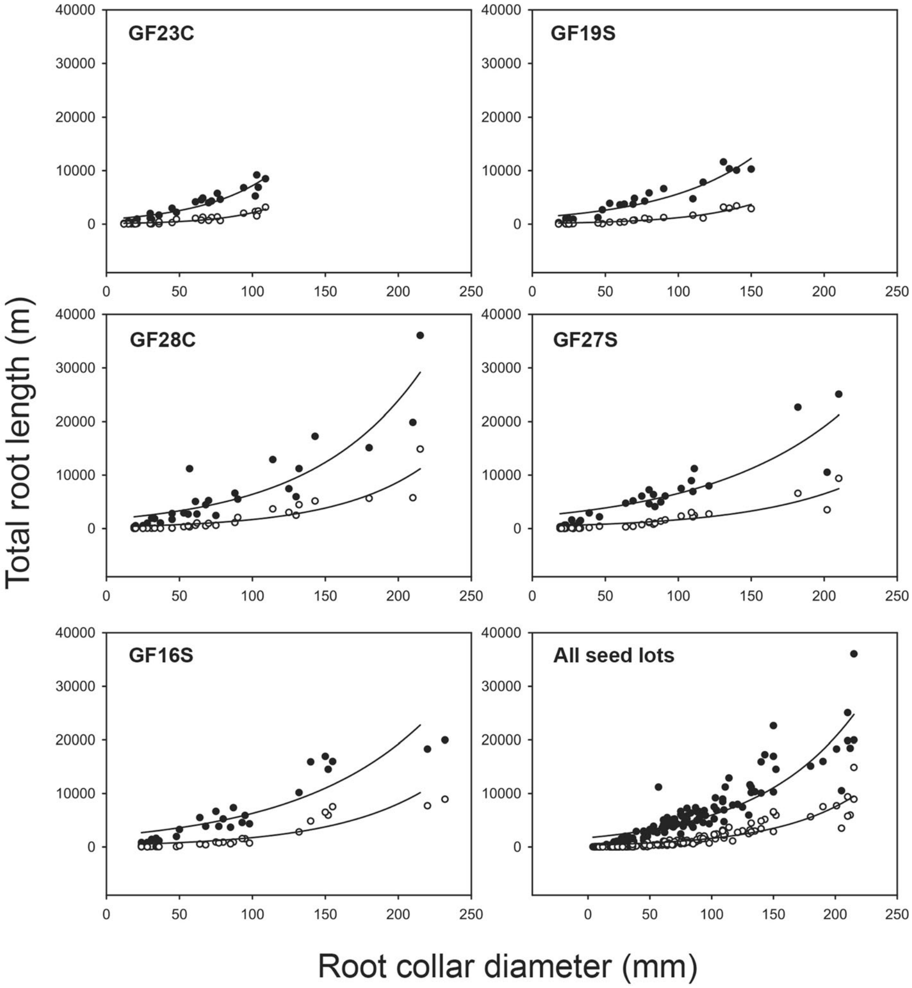

Fig. 8 Exponential growth and allometric relationships between regressions for RCD and total root length of >2-mm (*black circle*) and >5-mm (*white circle*) diameter for individual and all seed lots combined

However, where colluvial deposits were thin, the presence of bedrock at shallow depths severely affected root depth and architecture of several trees which had developed shallower and smaller than average root systems.

Root cross-sectional area (CSA)

By year 3 of the trial, the root cross-sectional area of vertical roots for each of the seed lots exceeded 100 $mm^2\ m^{-2}$, increasing to >150 $mm^2\ m^{-2}$ in year 4. A significant proportion ($P < 0.001$) of the total root CSA of year 3 trees (82%) and of year 4 trees (75%) was confined to the top 0.5 m of the soil profile (Figs. 12 and 13), Additionally, there was no significant interaction between depth and seed lot in year 3 ($P = 0.860$) or year 4 ($P = 0.872$), and when averaged across all of the depth increments, there was no significant difference in root cross-sectional area among seed lots in either year 3 ($P = 0.580$) or year 4 ($P = 0.185$). Although root CSA increased significantly with age, it also decreased significantly with depth (Figs. 12 and 13).

Although the CSA of the lateral roots was not measured, it is likely that its distribution would have mirrored the asymmetrical 'bilateral fan-shaped' architecture of the root length distribution (Fig. 14) with the highest values occurring within 0.5 m of the stump and in the upslope direction where individual roots were thicker than those in the downslope direction (Fig. 1d).

Root orientation

There was no indication that the orientation of total root length of 4-year-old trees (all seed lots combined) varied among seed lots. With respect to the slope contour, 48% of the total root length trended upslope of contour and 52% trended downslope of contour. However, relative to slope sector, the distribution of the lateral roots was

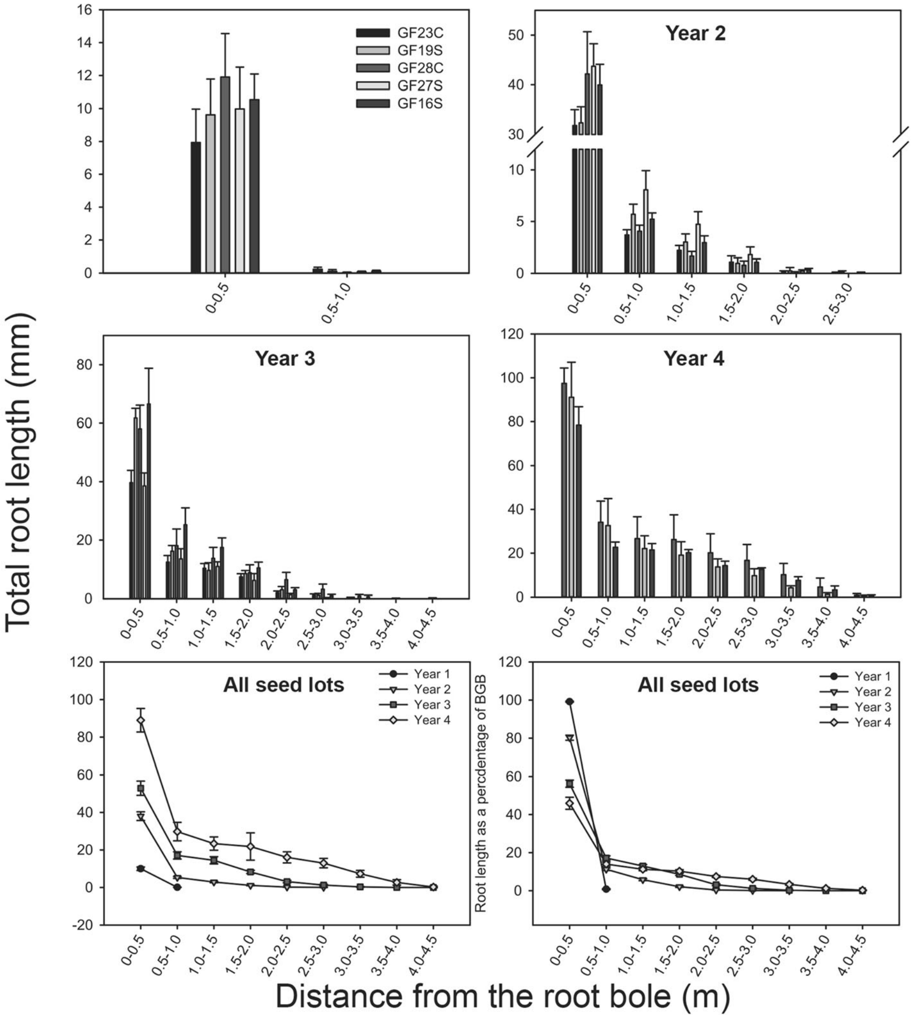

Fig. 9 Distribution of total length (m) of roots >2-mm diameter, for individual and all seed lots, in 0.5-m radial increments

highly asymmetric with the greatest proportion of the total root length trending between 45° and 90° (22%) and in the diagonally opposite direction between 225° and 315° (24%), respectively (Fig. 14). This is considered typical of the architecture of tree root systems that have developed on steep slopes and has previously been referred to as bilateral fan-shaped architecture (Chiatante et al. 2003) with the larger and stronger lateral roots in the upslope and leeward direction (Schiechtl 1980) (Fig. 1d) developing under compression (Stokes and Guitard 1997) and providing the greatest contribution to tree stability/anchorage (Sun et al. 2008). Conversely, roots located in the downslope and windward direction developed under tension are smaller and weaker and likely contribute less to tree anchorage. Similarly, Nicoll and Duncan (1996) report that more of the structural root mass of mature Sitka spruce (*Picea sitchensis* (Bong.) Carr.) were located on the leeward side than on the windward side of trees relative to the prevailing wind. At Okiwa, the bilateral fan-shaped architecture of the root systems of *P. radiata* has likely been influenced by exposure to the predominantly northerly winds as an adaptation to improve the rigidity of the soil-root plate and counteract their vulnerability to wind throw.

Canopy growth rates

There were no differences in canopy diameter among seed lots in any year of the trial (Additional file 2). There was however a significant increase ($P = 0.05$; data not shown) in canopy diameter (all seed lots combined) in each year of the trial increasing from 0.36 m in year 1 to 2.8 m in year 4, a rate of 0.7 m/year.

Root occupancy and canopy closure in relation to shallow landslide failure

Internationally and locally, it is well known that vegetation in general, and trees in particular, improve slope

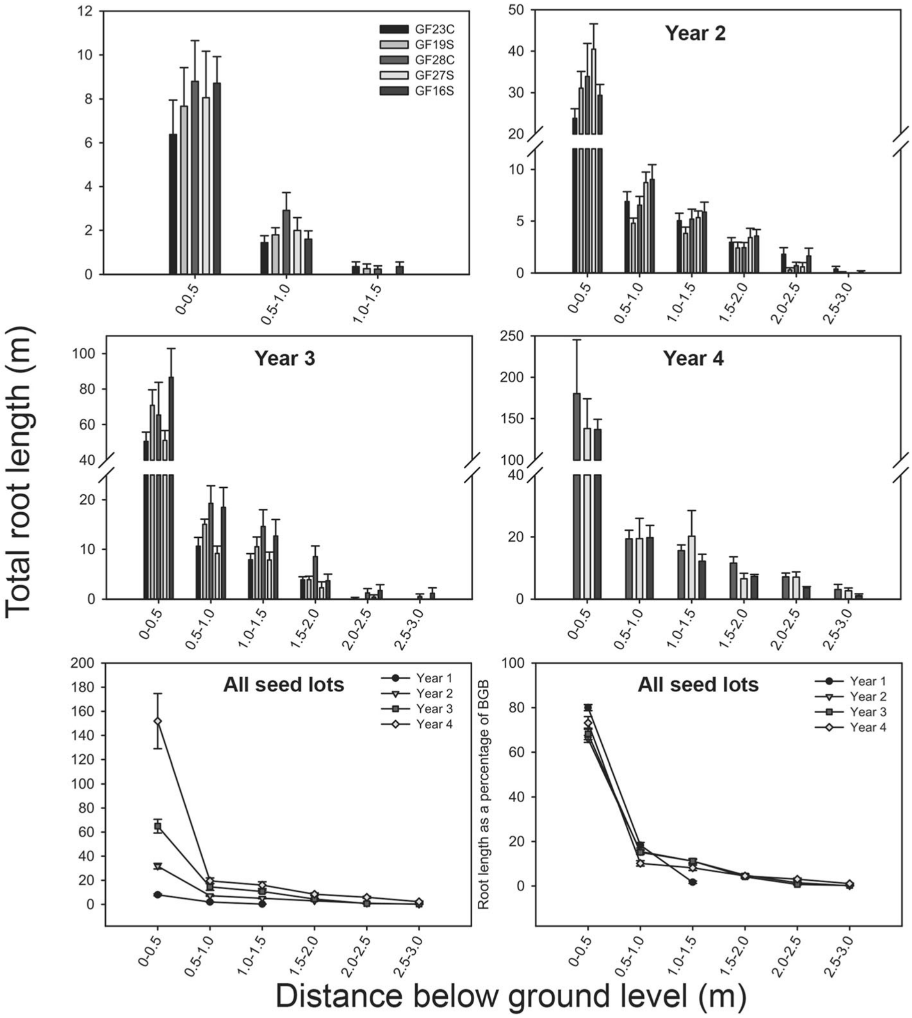

Fig. 10 Distribution of total length (m) of roots >2 mm for individual and all seed lots in 0.5-m depth intervals

stability and reduce erosion (e.g. Greenway 1987; Marden and Rowan 1993; Phillips and Marden 2005). The most common below-ground metrics used to compare the performance of different species for performing this erosion ‘protection’ or reinforcement function include root size, biomass, lateral spread, depth, cross-sectional area and the measurement of the strength of individual live, dead and decaying roots. In such studies, equal consideration is given to above-ground metrics including measurement of tree canopy growth (diameter) and its effects on the soil moisture regime of slopes largely through hydrological processes (e.g. interception, evaporation, transpiration) (Stokes et al. 2009). Tree roots reinforce soil making it stronger, and the canopy, through hydrological processes of interception and transpiration, tends to make the soil drier which increases soil strength. Both these factors tend to reduce the potential for slopes to fail. Species composition, growth rates, tree spacing and age influence the time (years after planting) at which plantings afford effective protection against the initiation of shallow landslides. Obviously, species that have fast growth rates and/or are planted at densities that enable root occupancy and canopy closure in the shortest time are intuitively likely to provide protection earliest. Findings from the few New Zealand field-based trials for *P. radiata* during its early growth period all show that the bulk of the below-ground biomass, total root biomass and total root length (roots >2 mm in diameter) is confined to the top 1 m of soil (Watson and O’Loughlin 1990; Watson and Tombleson 2002; this study), and most landslides in this terrain typically fail at ≤1-m depth (Marden et al. 1991; Page et al. 1994). Thus, despite significant increases in root spread and root depth (Additional file 10), biomass accumulation (Additional file 4) and gains in root cross-sectional area (Figs. 12 & 13), there would likely be insufficient lateral and/or vertical root development to prevent the initiation of shallow landslides should a major storm

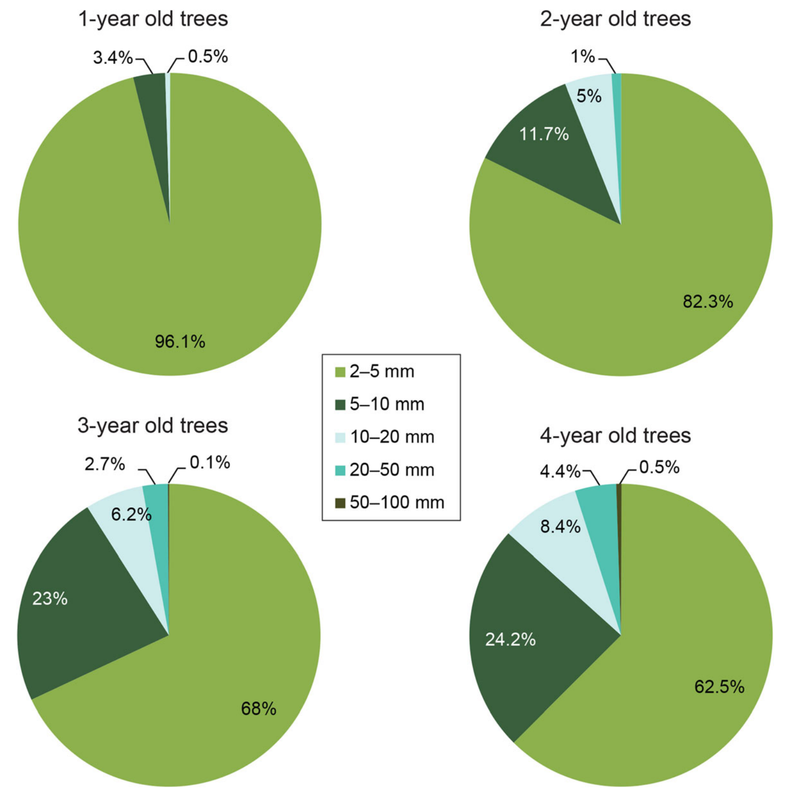

Fig. 11 Percent of total root length by root diameter (mm) for 1- to 4-year old *P. radiata*, all seed lots combined

event coincide with this early growth period. For example, although by year 3, roots had penetrated to a depth of ~2.5 m, by age 4 years, only ~4% of the total below-ground biomass (Additional file 6), 16% of the total root length (Additional file 9) and 4.5% of the total root CSA occurred below the typical 1 m failure depth of shallow landslides. Furthermore, as only ~8% of the total below-ground biomass (Additional file 7) and ~20% of the total root length (Additional file 8) overlapped with roots of adjacent trees, that is beyond a 2-m radius of the root bole (half the distance between rows), root reinforcement of soils between rows would be minimal, and thus, stands

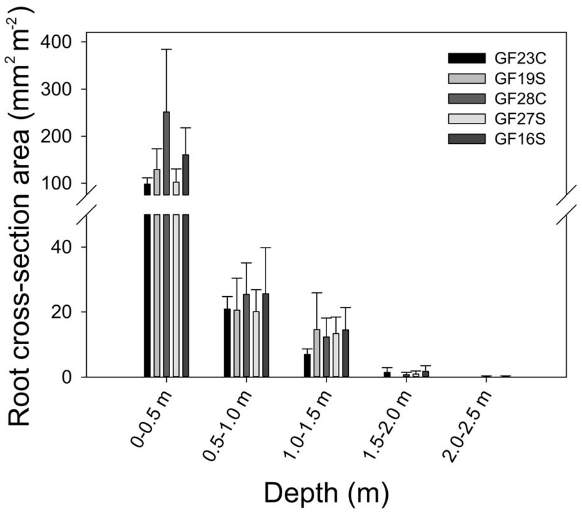

Fig. 12 Root cross-sectional area (mm^2 m^{-2}), by depth, for 3-year-old *P. radiata*. *Error bars* represent standard error of the mean

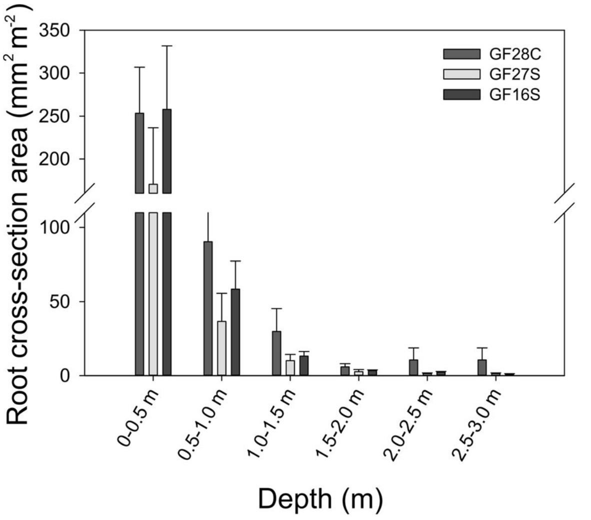

Fig. 13 Root cross-sectional area (mm^2 m^{-2}), by depth, for 4-year-old *P. radiata*. *Error bars* represent standard error of the mean

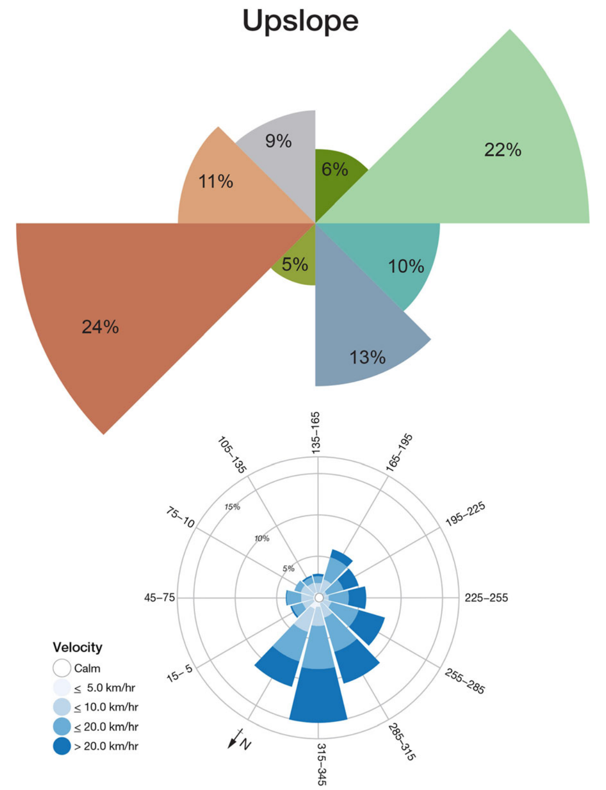

Fig. 14 Root orientation based on percent of total root length of 4-year-old *P. radiata*, all seed lots combined, in 45° segments relative to wind direction and velocity

of exotic pine would likely remain vulnerable to the initiation of shallow landslides beyond the age of 4 years. Indeed, field-based evidence shows that the incidence of landslides associated with stands of *P. radiata* following a major storm event (Cyclone Bola) in 1988 was an order of magnitude greater in stands 1–5 years old (established at ~1250 stems ha^{-1}), than for stands in the 6–8-year age class, and older (Marden and Rowan 1993). This suggests that between 4 and 8 years after planting, at a time when high-density stands are usually thinned to ~350 stems per hectare, there is a significant increase in the development of vertical roots, both below the stump and of sinker roots developed from laterals distal to the stump, including an increase in branching and diameter of individual structural roots. Whether this is purely a physiological response (age-related) or a function of reduced competition from neighbouring trees following thinning remains unclear. Nonetheless, Watson and O'Loughlin (1990) showed that the mean maximum radial distance of individual tree root systems within a thinned 8-year-old stand extended a distance of 4.7 m from the root bole, and the mean below-ground biomass averaged 37 kg per tree (radial and depth distribution not measured). A comparison with the Okiwa data suggests that within the 4–8-year growth period, radial roots could potentially extend a further 2 m from the stump, and the below-ground biomass of individual trees could potentially increase by ~75% to provide sufficient surface root reinforcement and anchorage to minimise the incidence of shallow slope failures during major storm events of a magnitude ≤Cyclone Bola.

The canopy, through hydrological processes of interception and transpiration, tends to make the soil drier which increases soil strength. Evaporation of rainfall from the canopy increases as the canopy develops. Planting density and canopy growth govern the time needed for canopy closure to occur. Historical evidence shows that dense stands afford earlier protection from storms and that the planting of exotic pines in a 4 × 2 m configuration affords faster control of existing erosion processes, particularly in areas with a high erosion risk, than do stands planted at lower stocking rates. At Okiwa, for stands planted at a density of 1250 stems ha^{-1}, the canopy radius of all seed lots increased at a similar rate of ~0.35 m per year such that the canopy of adjacent trees planted 2 m apart within a row touched within 3 years, and between-row closure (trees 4 m apart), would likely occur at about age 6–7 years. More recently, there has been a steady trend towards lower initial stocking rates, e.g. 833 stems per hectare (4 × 3 m spacing), with better quality nursery stock and establishment practices accounting, in part, for this trend. Based on the rate of canopy development at Okiwa, 'within-row' canopy closure would be delayed only marginally; however, this planting configuration does not address the 'between-row' risk to storm damage. Notwithstanding, a dense stand planted at a rectangular configuration can be configured to a more uniform spacing when thinned, usually within 5–8 years after planting, and though the canopy gaps widen, there is nonetheless sufficient root development at this time such that slope stability is not compromised. An alternative strategy to reduce the risk of the initiation of landslides between widely spaced rows is to (i) off-set every second 'within-row' tree such that trees in adjacent rows are not opposite each other; or (ii) align rows at right angles to the travel path of landslide debris, that is, along contour.

Annual evaporation from a closed-canopy forest in this region accounts for 85% of rainfall with interception at 35% (Pearce et al. 1987) and tree transpiration at 50% (Whitehead and Kelliher 1991), significantly reducing the risk of landslide initiation. Previously, (Kelliher, F. M., Marden, M., & Watson, A. J.: Stability of land and tree planting density East Coast, North Island, unpublished)[1] predicted canopy closure in a typical East Coast exotic forest would occur 8 years after establishment. Their modelling, however, was based on canopy growth data from a site altitudinally higher and with a colder climate (Grace et al. 1987) than at Okiwa. While our data suggest that canopy closure would likely occur between rows within 6–7 years, (Kelliher, F. M., Marden, M., & Watson, A. J.: Stability of land and tree planting density East Coast, North Island, unpublished)[1] acknowledged that elevation and associated climatic factors affect canopy growth rates so these should be taken into consideration when determining tree planting density. Thus, the overall effectiveness of a stand of *P. radiata* in reducing the potential for slopes to fail during extreme climatic events is primarily due to the combined effects of soil-root reinforcement and canopy development which, in turn, is predominantly dependent on planting density and the influence of environmental factors on growth. Acknowledging that irrespective of the planting density, and in the event of a major storm, *P. radiata* would afford little protection against the initiation of landslides during, at least the early establishment years, it is nonetheless clear from published literature that the occurrence of landslides initiated during Cyclone Bola was considerably reduced in stands once canopy closure has been attained. Although rainfall interception by the canopy during such events is minimal, it is around the time at which canopy closure occurs that the root systems afford effective root–soil reinforcement sufficient to minimise the initiation of shallow landslides.

Conclusions

Our primary aims were to: (i) provide field-based, root-related data and allometric relationships for each of five different seed lots of *P. radiata* as inputs for slope stability and/or soil reinforcement modelling, many of which suffer from a paucity of the types of data collected in this study, particularly for juvenile (≤8 years old) trees; (ii) establish whether or not there were significant differences in the growth rate among seedlings and cuttings grown from seed lots available at the time of early forest establishment in this region (1960s onwards), and planting stock (both seedlings and cuttings) grown from genetically improved seed lots available in more recent times; and then (iii) based on the findings, evaluate whether or not there is sufficient evidence in support of amending the current planting density recommendations for erosion-prone hill country likely to be afforested in the future.

This study provides much needed field-based, root-related data and allometric relationships for *P. radiata* as inputs for slope stability and/or soil reinforcement modelling (e.g. Ekanayake and Phillips 1999; Schwarz et al. 2010), many of which suffer from a paucity of this type of data, particularly for juvenile (<8 years old) trees (Phillips et al. 2012). While model development has in recent years focussed on the contribution of lateral roots to slope reinforcement, the findings of this study suggest that for species which develop vertical tap and sinker roots (e.g. *P. radiata*), 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 a component of future model development.

As there was no consistent evidence of significant differences in total above- or below-ground biomass, maximum root spread or maximum root depth between planting material type (seedlings or cuttings) or between the earliest and the later genetically improved seed lots during the early 4-year post-establishment period, we conclude that no one seed lot would provide earlier soil reinforcement or result in a superior level of slope stability than would any of the other seed lots trialled. Indeed, of the three seed lots trialled through to year 4, none had developed more than ~4% of their total below-ground biomass, 16% of their total root length and 4.5% of their total root CSA (vertical roots only) below the typical 1-m failure depth of shallow landslides. Additionally, as only ~8% of the total below-ground biomass and ~20% of the total root length overlapped with roots of adjacent trees, between-row root reinforcement would be minimal, and thus, stands of exotic pine are likely to remain vulnerable to the initiation of shallow landslides beyond the age of 4 years—a conclusion supported by previous research on storm-initiated, landslide-vegetation relationships for *P. radiata* (Marden et al. 1991; Phillips et al. 1991; Marden and Rowan 1993). Although the conclusions drawn are based on a relatively small numbers of sample trees and the study period was limited to their early growth period (i.e. years 1 to 4), there is nonetheless sufficient evidence to suggest that a reduction in the recommended planting density for steep hill country prone to the initiation of shallow landslides would further prolong the period of vulnerability of young plantings to a greater risk of damage by landslides and at a time when storm events are predicted to become more frequent. Thus, irrespective of seed lot preferences, the current recommended planting density of 1250 stems ha^{-1} remains the most effective and quickest means of reducing the risk of landslide initiation in areas of erosion-prone hill country. However, it must also be acknowledged that differences among seed lots are more likely to become apparent at a later age and become more marked as the trees mature. Further excavations of trees in the 5–8-year age range would be needed to verify this and before any consideration is given to reducing the currently recommended planting density for erosion-prone East Coast hill country.

Endnotes

[1] Kelliher, F. M., Marden, M., & Watson, A. J. (1992). Stability of land and tree planting density East Coast,

North Island ([Forest Research Institute Contract Report FWE 92/13]. Rotorua, New Zealand).

[2] Site index refers to the timber potential for a site for a particular species, usually at a fixed age somewhere near the expected rotation length for the species. In forestry, the usual method to develop site index is from stand height records, as good site quality is often reflected in good height growth (Clutter et al. 1983; Maclaren 1993).

[3] Hockey, M., & Page, M. (1983). Site index data for the Gisborne-East Coast region. Collated 1981 and partially revised in 1983. Wellington: Unpublished Internal New Zealand Forest Service Report, New Zealand Forest Service.

Additional files

Additional file 1: Plot design planted at 1250 stems per hectare. (DOC 125 kb)

Additional file 2: Mean height, DBH, RCD, canopy diameter, AGB and BGB, individual seed lots. (DOC 75 kb)

Additional file 3: Mean foliage, branch, stem, root and root bole biomass, individual seed lots. (DOC 73 kb)

Additional file 4: Mean above- and below-ground component biomass, biomass totals and biomass ratios, all seed lots combined. (DOC 40 kb)

Additional file 5: Summary of analysis parameters (slope, intercept, R^2, standard error of estimate), for root collar diameter against root biomass and root length for roots >2- and >5-mm diameter, individual seed lots. (DOC 47 kb)

Additional file 6: Mean root biomass (g) distribution below-ground level, and percentage of the total below-ground biomass, all seed lots combined. (DOC 41 kb)

Additional file 7: Mean root biomass (g) distribution with increasing horizontal distance (radius) from the root bole, and percentage of the total below-ground biomass, all seed lots combined. (DOC 45 kb)

Additional file 8: Mean root length (m) distribution with increasing horizontal distance (radius) from the root bole, and percentage of the total root length, all seed lots combined. (DOC 37 kb)

Additional file 9: Mean root length (m) distribution below-ground level, and as a percentage of the total root length, all seed lots combined. (DOC 33 kb)

Additional file 10: Mean maximum root depth and spread of roots >2-mm diameter, all seed lots combined. (DOC 31 kb)

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Authors' contributions

MM was the primary author. MM and DR undertook the fieldwork. DR compiled the data into spreadsheets. SL completed the statistical analyses. All authors read and approved the manuscript.

Competing interests

The authors declare that they have no competing interests.

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