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Manatū Ahu Matua

Plot-based, growth performance of space-planted mānuka (*Leptospermum scoparium*) on marginal land, and vulnerability to erosion

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- In 2015 and again in 2016, at two study sites, growth metrics were collected for three age classes of space-planted mānuka to determine the effect of planting density on the time (years after planting) required for such plantings to provide an effective erosion control function when established on marginal land.
- In 2015 this project was jointly funded by the Ministry for Primary Industries (MPI) and Landcare Research Capability funds. The latter funds were used to collect basic root metric data. In 2016 funding was provided by the Ministry for Primary Industries supplemented with funding by Landcare Research (Sustainable Land Use Initiative) via Plant and Food Core funding, and Gisborne District Council.

Objectives

- In 2015, secure access to established plantation-style, space-planted, mānuka at Lake Tutira and Puketoro Station, identify and map landform units present within these study sites. Establish Permanent Sample Plots (PSP) on the different landform units, and measure in situ above-ground growth metrics of mānuka.
- In 2016, revisit these Permanent Sample Plots, re-measure in situ mānuka growth metrics, and remove sample trees for analysis of their root systems.
- Compare the above-ground and root growth metrics of mānuka across different landforms at each site.
- The long-term objective is to assess when (years after planting) space-planted mānuka could potentially reduce the "vulnerability' of these sites to erosion.

Methods

- In 2015, three (20 × 20 m) Permanent Sample Plots were established across 3 landform units within an area planted at Lake Tutira in 2012; and one plot was established in an area planted in 2011, a total of 10 plots. A further 3 plots were established on each of 3 different landforms within an area planted on Puketoro Station in 2013, a total of 9 plots.
- In 2015, and again in 2016, tree height, diameter at breast height (DBH), root collar diameter (RCD) and canopy spread (diameter) were measured for all individual trees within each plot. These parameters were also measured for all naturally reverted plants, mostly kānuka, found within the plots. Dead and missing trees were accounted for.
- Sample trees were removed from beyond the bounds of selected plots for analysis of their root systems and apportionment of above and below ground biomass. Mean plant biomass (dry weight) was used to approximate total stand biomass by age class and landform, and rate of biomass production for comparison with stands of natural reverting kānuka of equivalent age.
- Data from PSP plots on each of the different landforms were averaged and the results used to assess possible site influences on mānuka growth performance.
- Measurement of canopy and root spread (diameter) were used to estimate the approximate time required for space-planted mānuka established at different spacing to reach canopy closure, and root occupancy for comparison with individual trees of equivalent age within naturally reverting stands of kānuka.

Results

- In 2016, all 19 plots were revisited and plants (planted mānuka and reverted kānuka) within the bounds of each plot were measured.
- At Lake Tutira, the metrics used for measuring above-ground growth performance (tree height, DBH, root collar diameter, canopy spread) of mānuka planted in 2011 and 2012 indicate that since 2015, and across the different landforms, there has been a significant increase in growth performance but the growth performance between landforms is not significantly different. On account of the greater root collar diameter but stunted stature of the 2011 plantings, it would appear the latter were slower to establish because of the greater altitude and/or exposure of this permanent sample plot.
- Similarly, at Puketoro Station there has been a significant increase in the above-ground growth performance since 2015, particularly of mānuka established on slump topography and stable interfluves, but the growth performance between landforms is not significantly different. Growth on earthflows continues to be inhibited by increased wetness, ground movement, and light suppression by tall sedge-like plants associated with poorly drained sites.
- Mortality at both the Lake Tutira and Puketoro Station sites did not differ between 2015 and 2016 data sets, and due to the large variability in mortality between the replicates on each landform, there was no significant difference between the landforms with respect to mortality at either site. In 2016, mānuka mortality remained unsatisfactorily high on the wetter and more mobile earthflow sites at Puketoro Station (51±18%), and on the shallow-soiled landslide scars at Lake Tutira (26±23%). Mānuka mortality is less on the more stable interfluves averaging 17±17% at Tutira, though not statistically significantly different when compared with 33±7% on interfluve ridges, and 28±8% on slump topography at Puketoro Station.
- Based on the number of live trees present at the time of measuring in 2016, the overall density of surviving mānuka at Lake Tutira remains unchanged and averages 1000 stems ha^{-1}, and at Puketoro Station, 1100–1200 stems ha^{-1}.
- At Lake Tutira, canopy closure for plantings spaced at 4 m (between rows) × 3 m (within row spacing between plants) and assuming a constant canopy growth rate of ~0.3 m (radius) per year based on the difference in canopy dimensions between 2015 and 2016, canopy growth appears to be marginally slower than for equivalent aged kānuka though potentially on track to achieve canopy closure 7–8 years after establishment but will be patchy, especially in areas where landslide scars are densest.
- At Puketoro Station, for the mānuka plantings established in 2013, the mean canopy radius in 2016 was just ~0.25 m, and unchanged since 2015, but is nonetheless similar to equivalent-aged kānuka. Canopy growth rates will likely improve as mānuka plantings emerge above the rank grass but at 3 × 3 m spacing canopy closure will be considerably delayed given the less favourable growing conditions of altitude, wet earthflow landforms, higher proportion of unstable landforms, and higher initial mortality.
- The mean maximum root spread of the lateral roots of mānuka planted in 2011 at Lake Tutira was ~3.5 m. There were no significant differences in root spread between the 2011 plantings, and the 2012 plantings on stable interfluves or colluvial slopes. Whereas the root spread of the 2012 mānuka plantings on landslide scars (~1 m), though not significantly different from the same age plantings on stable interfluves and colluvial slopes, their root systems were nonetheless considerably more compact than those of the 2011 plantings. At Puketoro, the mean maximum root spread of the 2013 plantings was <0.6 m and was not significantly different across the three landforms present at this location.

- The oldest (2011) mānuka plantings at Lake Tutira had a mean maximum rooting depth of ~1.1 m. There were no significant differences in rooting depth between the 2011 and 2012 plantings on the stable interfluves or between each of the landforms planted in 2012. Additionally, the rooting depth of mānuka on colluvial and landslide scars, though not significantly different from each other (~0.5 m), is significantly shallower than for the 2011 plantings. The mean maximum rooting depth of the 2013 mānuka plantings at Puketoro is~ <0.25 m, and was not significantly different across the three landforms present at this location.
- The above ground biomass of mānuka plantings at Lake Tutira was not significantly different between landforms or between the 2011 and 2012 plantings and comprised >80% of total plant biomass. Similarly, at Puketoro Station the above ground biomass of mānuka was not significantly different between landforms and for these younger plantings comprising >80% of total plant biomass.
- At Lake Tutira, and irrespective of the age of mānuka plantings, there were no significant differences in total below ground biomass between any of the landforms with root biomass comprising <20% of total plant biomass. Similarly, because of the high variability in the total below ground biomass of the 2013 mānuka plantings at Puketoro Station, it was not significantly different across the three landforms, and root biomass of these younger plantings comprised <20% of total plant biomass.
- The root: shoot ratio of mānuka plantings at Lake Tutira was not significantly different between landforms or between the 2011 and 2012 plantings. Similarly, at Puketoro Station the root: shoot ratio of mānuka was not significantly different between landforms.
- Mean total plant biomass of mānuka plantings at Lake Tutira and Puketoro Station were not significantly different between the landforms present at these respective sites. Similarly, at Lake Tutira there was no significant difference in mean total plant biomass between the 2011 and 2012 plantings. As at 2016, differences in total stand biomass between the 2011 and 2012 plantings at Lake Tutira were not significantly different or between the 3 landforms planted in 2012 and ranged between 1115 kg/ha and 3719 kg/ha. There were also no significant differences between the total stand biomass at the Puketoro Station site, where biomass ranged between 80 and 244 kg/ha. At Lake Tutira, the annual rate of biomass production of the 2011 mānuka plantings for the 5-year period since establishment was 744 kg/ha/year. This suggests the rate of biomass production of space planted mānuka is significantly less than that of naturally reverting stands of kānuka of equivalent age at~6000 kg/ha/year (unpublished data), and is a function of the lower stand densities at this site. Similarly, at Puketoro Station the highest annual rate of biomass production of the 2013 mānuka plantings for the 3-year period since establishment was 101 kg/ha/year. Again, the rate of biomass production at this site at~27 000 kg/ha/year (unpublished data) is significantly less than that of naturally reverting stands of kānuka of equivalent age where stand densities can be up to 100 times higher than for areas established with space-planted mānuka.
- There was no significant difference in total carbon accumulation of planted mānuka across different landforms at either site. At Lake Tutira it ranged between 0.56 t/ha and 1.86 t C/ha, and at the Puketoro Station site carbon accumulation ranged between 0.04 and 0.15 t/ha.
- There was no significant difference in total CO_2 /ha of planted mānuka across different landforms at either site. At Lake Tutira it ranged between 0.92 and 3.07 t $C0^2$/ha, and at the Puketoro Station site carbon accumulation ranged between 0.07 and 0.25 t $C0^2$/ha.
- At this early stage of growth (3-5 years after establishment), the above- and below-ground growth performance of space-planted mānuka at Lake Tutira and Puketoro Station is of the same order of magnitude as for individual trees within a naturally reverting kānuka

stand of comparable age but higher density. However, the level of erosion mitigation against landslide initiation once canopy closure and full root occupancy has occurred will not be as effective as has been shown for stands of naturally reverting mānuka and kānuka because of the lower stocking density. Space-planted mānuka will therefore remain vulnerable to storm influences for some undefined time after canopy closure.

Recommendations

- As there are few records of the above-and below-ground growth performance of mānuka and kānuka established as low-density, plantation-style plantings, further data collection of growth metrics (e.g. DBH, collar diameter, tree height, canopy diameter) from the permanent sample plots established at Lake Tutira and at Puketoro Station is recommended. Further data are required to model the rate of canopy closure and root occupancy for mānuka at the respective planting spacing established on the different landforms associated with these two study sites.
- As the trees age, the effort and cost of data collection will increase exponentially. To spread the cost and workload it is suggested that MPI, in conjunction with Landcare Research, develop and agree to a multi-year work plan to year 2020. For the Lake Tutira plantings it is recommended that data collection continue annually until 2020. This would provide continuity in the time-series data collected to date, and importantly, span the period (years 5-7 after planting) when it is suspected that significant biomass is allocated to the development of anchoring roots. Additionally, it is suggested that sampling be restricted to only those permanent sample plots established within the 2012 age class (9 plots in total). At Puketoro Station it is suggested that data are collected from the 9 permanent sample plots every second year, that is, in 2018 (5-year-old mānuka) and 2020 (7-year-old mānuka). By 2020 trends and differences in growth performance in canopy closure and root occupancy across different terrains present at both these locations will be clear, and the time-series data collected will be invaluable for modelling the effectiveness of these plantings in mitigating shallow landslides and mass movement processes.
- Extend the study to other regions where significant areas of marginal land have been or are likely to be planted in mānuka, e.g. Northland, Taranaki, Wairarapa, and Manawatū-Wanganui, and where regional variations in growth could influence the timing of canopy closure, effective root-soil occupancy and thus the vulnerability of slopes to storm effects.
- With the introduction of a new Afforestation Grant Scheme (AGS), and the potential for further establishment of mānuka for honey production, plot-based data of above- and below-ground mensuration rates, particularly during the early growth period following planting, will be of value to the national carbon (C) inventory system, and policy to reduce net greenhouse gas emissions. Growth metrics from these plots would provide data for the development of mānuka-specific allometric equations for calculating carbon sequestration more accurately than is possible using generalised mixed-species equations developed for older natural forest stands.
- As a means of promoting rates of mānuka growth and survival, evaluate the effectiveness of practices used to suppress grass competition (e.g. pre-plant spot spraying, post-plant release spraying), and trial the periodic grazing of mānuka to prevent the development of rank grass.
- Plant mānuka at densities that will achieve the desired final stocking, allowing for mortality on sites affected by past and current erosion.

1 Introduction

In the East Coast Region of the North Island, the space-planting of mānuka is considered to be a legitimate erosion mitigation measure for which funding is available through the Erosion Control Funding Programme (ECFP), formerly the East Coast Forestry Project, and approved by the Ministry for Primary Industry (MPI). Here, the ‘worst of the worst eroding land’, identified as Land Overlay 3 in Gisborne Council’s District and Regional Plan, is dominated by deep-seated earthflow and slump failures. Elsewhere throughout New Zealand, space-planted mānuka is being established on steep and marginal hill country, which in many places is susceptible to surface erosion processes, particularly shallow landslides. Typically, and on account of their high current erosion rates, these areas are classified in the New Zealand Land Resource Inventory (National Water and Soil Conservation Organisation 1975) as Land Use Capability (LUC) Class 7. The expectation is that space-planted mānuka will provide effective and long-term, erosion control.

While not disputing claims that plantation-style plantings of mānuka will in time reduce the erosion susceptibility of marginal land, there is little quantitative evidence, especially for different plant spacing specifications, with which to establish the time (years after planting) slopes are likely to remain ‘at most risk’ to storm-related damage. High planting density specifications are likely to have an economic impact on honey and oil extraction incurred by the additional establishment costs, and reduced levels of production, with canopy closure occurring earlier than if planted at a wider spacing. The overlapping of individual tree canopies and eventual canopy closure will likely supress flowering development, and thus honey production is expected to decline and then plateau thereafter. Conversely, the erosion control effectiveness of mānuka will likely be compromised if the planting density is too low. Thus in areas of marginal land where erosion susceptibility is high, a tension exists between deriving economic gains from honey and oil extraction, and the erosion control effectiveness of these plantings.

Much of the research relevant to understanding the erosion control effectiveness of mānuka has largely been derived from investigations of ‘stands’ of naturally reverted scrub and/or of individual trees extracted from these stands. At the stand level, previous studies have included investigations of water balance components (e.g. interception of rainfall) (Aldridge & Jackson 1968; Rowe et al. 1999), the mitigation of storm-effects (e.g. landslide prevention) by closed-canopy stands of scrub (Marden & Rowan 1988, 1993; Hicks 1991; Bergin et al. 1995), and their use as a bio-engineering agent on roadsides and in mining rehabilitation (Watson et al. 1998). Studies of individual trees have involved the measurement of root growth (spread, depth and biomass) (Watson & O’Loughlin 1985; Watson et al. 1994), rates of root decay (Watson et al. 1997, 1999) and of root tensile strength (Watson & Marden 2004). Thus, previous attempts to model soil–root reinforcement and slope safety factor (Watson & O’Loughlin 1985; Ekanayake et al. 1997, 2004; Watson et al. 1999) are based largely on data from fully stocked stands of scrub where the tree density is initially high, and for young regenerating stands can be as high as 97 000 stems ha^{-1} (unpublished data).

2 Aim and Purpose

To our knowledge there have been no studies of a similar nature undertaken of stands or of individual plants established as widely spaced plantings, let alone for plantings established on marginal land. As there was no published research data currently available on the growth rates (both above- and below-ground) of space-planted mānuka with which to determine when (years after establishment) such plantings are likely to provide an effective erosion control function, a pilot study was initiated. The aim of this study was to establish Permanent Sample Plots [PSP] on marginal land at two study sites with contrasting landforms, and from which mensuration data could be collected over successive years.

These data will greatly assist in understanding the effects of planting density, survival rates and landform on the efficacy of space-planted mānuka to reduce the "vulnerability" of marginal land to slope failure through effective root-reinforcement, and protection by a closed canopy. In addition, with the introduction of a new Afforestation Grant Scheme (AGS), and the potential for further establishment of mānuka for honey production, plot-based data of above- and below-ground mensuration rates, particularly during the early growth period following planting, will be of value to the national carbon (C) inventory system, and to policy to reduce net greenhouse gas emissions.

3 Study site

Lake Tutira (Fig. 1) and Puketoro Station (Fig. 2) were selected as study sites to assess the erosion control effectiveness of space-planted mānuka. Both sites are classified as LUC Class 7, marginal land, in the New Zealand Land Resource Inventory (NZLRI, 1975) and each has landforms that are susceptible to different erosion processes. Importantly, mānuka had already been established at Puketoro Station in 2013, and at Lake Tutira in 2011 and 2012 before this study began. The physical site characteristics at these study sites are listed in Table 1.

Table 1 Physical site characteristics from the New Zealand Land Resource Inventory for Lake Tutira and Puketoro Station

	Lake Tutira	Puketoro Station
LUC Class	7e3[1]	7e19[2]
Slope group	E (21–25^{0}) & F (26–35^{0})	E (21–25^{0})
NZ Soil Classification[3]	Typic Immature Pallic, Typic Orthic Allophanic	Typic Orthic Allophanic
Geology[4]	Pliocene-age mudstone, sandstone, limestone	Mélange of the East Coast Allochthon
Erosion severity and type	Extreme shallow landsliding, slight tunnel gullying	Extreme earthflow, very severe gully, moderate slump
Vegetation type	Low producing pasture	High producing pasture
Elevation (asl)	200–375 m	600–700 m
Aspect	West facing	North facing

[1] Page (1976)

[2] Jessen et al. (1999)

[3] Hewitt (2010)

[4] Mazengarb & Speden (2000)

For the planted areas, landscape units were identified and mapped. At Lake Tutira, three landforms have been identified: (i) landslide scars with thin, skeletal soil/colluvial materials, predominantly located on mid-slopes (11.5 ha, 27.4% of study area); (ii) colluvial slopes where landslide debris comprising thick deposits of mixed soil and colluvium has accumulated (4.9 ha, 11.5% of study area) (Fig. 3); and (iii) stable interfluve ridges and spurs, with little sign of slope instability and where thick forest soil and volcanic ash cover beds have remained intact (22.3 ha, 53% of study area). Plots were not established on areas of alluvial valley floor (0.65 ha, 1.5% of study area) or on slopes so 'disturbed' it was difficult to identify a specific landform unit on which to locate a permanent sample plot (2.78 ha, 6.6% of study area).

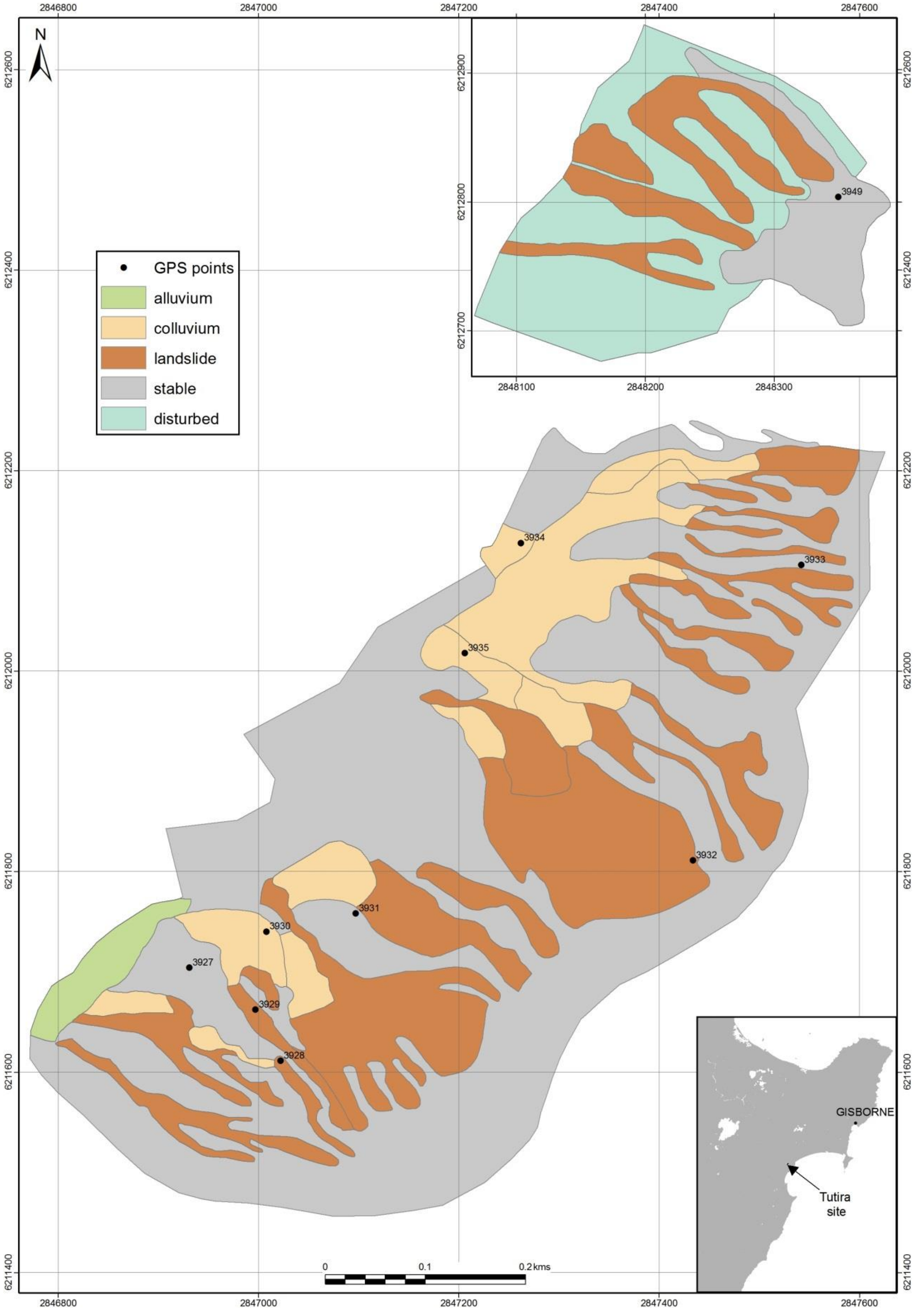

Figure 1 Map showing the location of permanent sample plots established within space-planted mānuka plantings established in 2011 (inset) and 2012 (large area), relative to the different landform units at Lake Tutira.

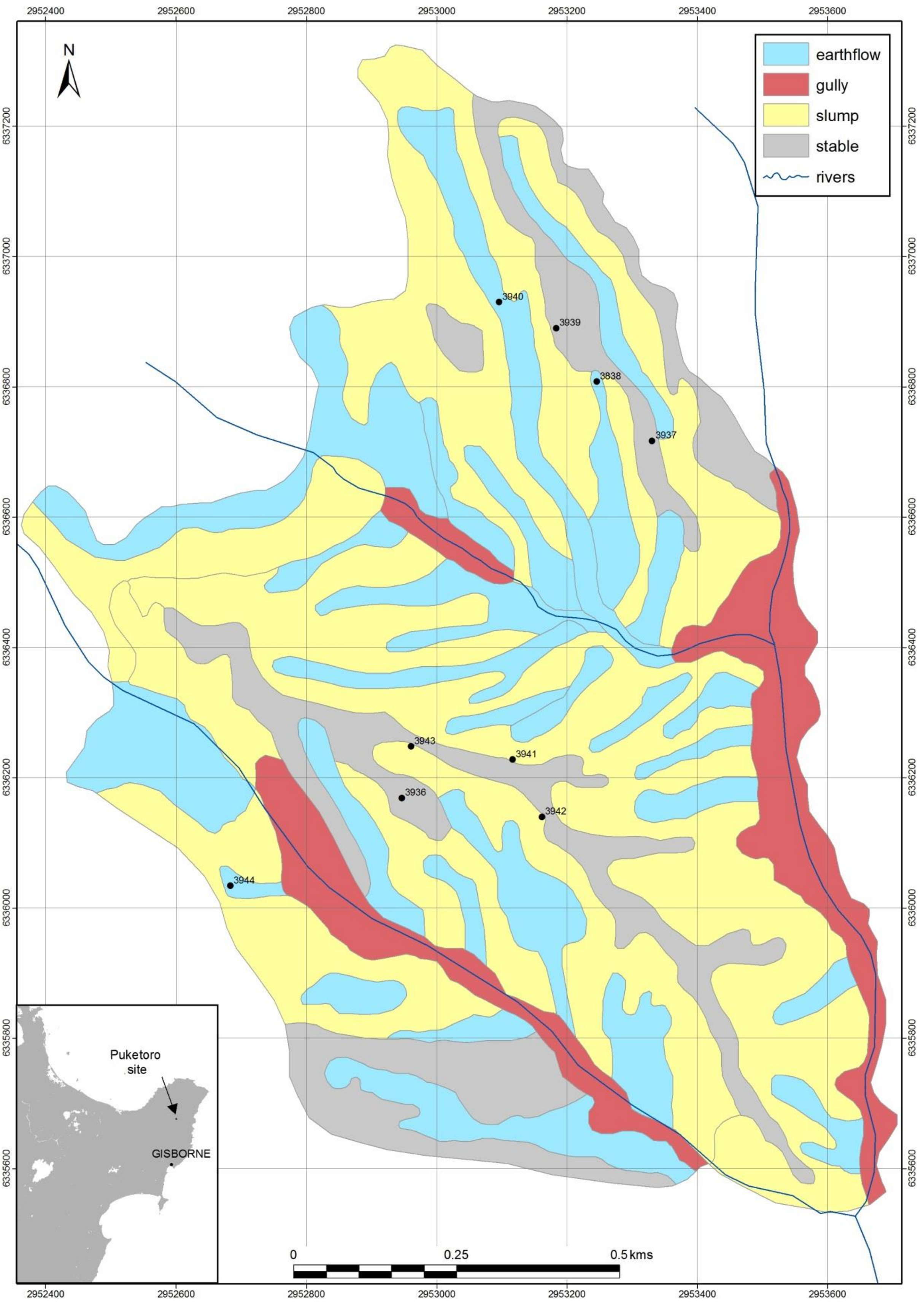

Figure 2 Map showing the location of permanent sample plots established within space-planted mānuka plantings established in 2013, relative to the different landform units at Puketoro Station.

Figure 3 Mānuka planted in 2012 on a colluvial foot slope at Lake Tutira. The colluvial soils have been derived from the landslide scars further upslope.

Figure 4 Measuring mānuka on colluvial slope at Lake Tutira in 2016.

At Puketoro Station, landforms include: (i) earthflows, overgrown with sedge-like vegetation and where downslope surface displacement is likely during winter months (37.4 ha, 27.5% of study area) (Fig. 5); (ii) slump topography showing signs of slope movement, both past and present (64.2 ha, 47.2% of study area); and (iii) stable interfluve ridges and spurs (20.6 ha, 15.2% of study area). Actively eroding gullies comprising 10.1% of the study area were not planted in mānuka.

Figure 5 Mānuka planted in 2013 on earthflow terrain (foreground) at Puketoro Station.

4 Permanent Sample Plots (PSP plots)

At Lake Tutira, three permanent sample plots (each 20 × 20 m) (Hurst & Allen 2007) were established on each of three different landforms within an area planted in 2012 and one plot was established within an area planted in 2011 (Fig. 1). Similarly, at Puketoro Station, three replicate plots were established on each of three different landforms within an area planted in 2013 (Fig. 2).

Plots were established between March and May (2015). The centre point of each plot is marked with a wooden post. An aluminium tag with an identification number (Appendix 1) was nailed to the top of the post. A tall, white fibreglass rod was placed next to the post. The location of the centre point of each plot was fixed using Global Positioning System technology (GPS); GPS coordinates for the PSP plots are listed in Appendix 1.

In 2015, and again in 2016 all live trees including natural regenerating plants within each plot were measured for diameter at breast height (DBH at 1.4 m above ground level on the upslope side of each tree), root collar diameter (RCD, measured at ground level), plant height, and maximum projected canopy spread (measured in two directions and averaged). Where multiple seedlings had all survived and grew as a 'cluster' of individual plants, each with its own root system; stem height, RCD and DBH was measured for each stem. Plants that had died since planting were counted. Table 2 presents details of the number of plots established per landform and the total number of trees measured at each of the study sites.

Table 2 Summary of the number of plots established per landform, trees measured and number of measurements collected at the two study sites

	Lake Tutira		Puketoro Station
Age class	2011	2012	2013
Landforms	1	3	3
Plots per landform	1	3	3
Number of plots	1	9	9
Trees measured	39	346	378

In 2016, as a measure of root spread and depth development 3 sample trees were excavated from outside the bounds of each sample plot at Puketoro, totalling 27 trees. At Lake Tutira, and on account of the large size of the plants, it was decided to extract 3 plants representative of trees associated with each of the three landforms planted in 2012, and a further 3 trees from the site planted in 2011 – a total of 12 trees. For each sample tree, tree height, canopy spread, root collar diameter (RCD) and diameter at breast height (DBH) (where applicable) were measured. Canopy spread was taken as the mean of the diameter measured in two directions at right angles. Trees were cut at ground level and the above-ground components separated into branches, foliage and stem. Root system extraction and measurement methods followed well-established procedures (e.g. Watson et al. 1999; Marden et al. 2005; Phillips et al. 2014, 2015). Once removed from the ground the root system of each plant was washed to remove adhering soil matter then photographed (Fig. 6). A recovery efficiency of 90% was estimated for roots ≥1 mm diameter and 80% for roots <1 mm (fibrous). Below-ground growth parameters included mean root depth and mean root spread of the lateral roots, hereafter referred to as root depth and root spread. The latter was taken as the mean of the maximum root length measured from root tip to root tip in two directions at right angles to each other.

All plant components, both above- and below-ground were oven-dried at 100° C for at least 48 h or until no further weight loss was detectable then weighed to the nearest 0.1 g. Biomass and root: shoot ratios were calculated using dry mass. The conversion from C to Co^2 is based on C x 1.65.

Figure 6 Canopy and root system of a 5-year old (planted in 2011) mānuka at Lake Tutira.

5 Results

5.1 Planting density at the time of establishment

5.1.1 Lake Tutira

Mānuka was contracted to be planted at 4 × 3 m spacing (James Powrie, pers. comm., Hawke's Bay Regional Council), that is, at a planting density of 833 stems ha^{-1}. However, field data collected from PSP plots in 2015 indicated the planting spacing may have been closer to 3 × 3 m. Accounting for gaps where trees were probably planted but are now missing, the mean number of live plants measured within the bounds of the PSP plots suggests the actual planting density at the time of establishment was 1075 stems ha^{-1} for the stable ridges/spurs, 1275 stems ha^{-1} for the depositional colluvial slopes, and 1300 stems ha^{-1} on the areas identified as former landslide scars.

5.1.2 Puketoro Station

Mānuka was contracted to be planted at 3 × 3 m spacing, that is, at a planting density of 1,111 stems ha^{-1}. As per Lake Tutira, field data from PSP sites indicates a higher density at the time of establishment. This likely averaged 1750 stems ha^{-1} on the stable interfluves, 1325 stems ha^{-1} on slump topography, and 1600 stems ha^{-1} on areas identified as earthflows.

5.2 Mortality since establishment

Mortality at both the Lake Tutira and Puketoro Station sites did not differ between 2015 and 2016 data sets, and due to the large variability in mortality between the replicates on each landform, there was no significant difference between the landforms with respect to mortality at either site (Figs 7 & 8).

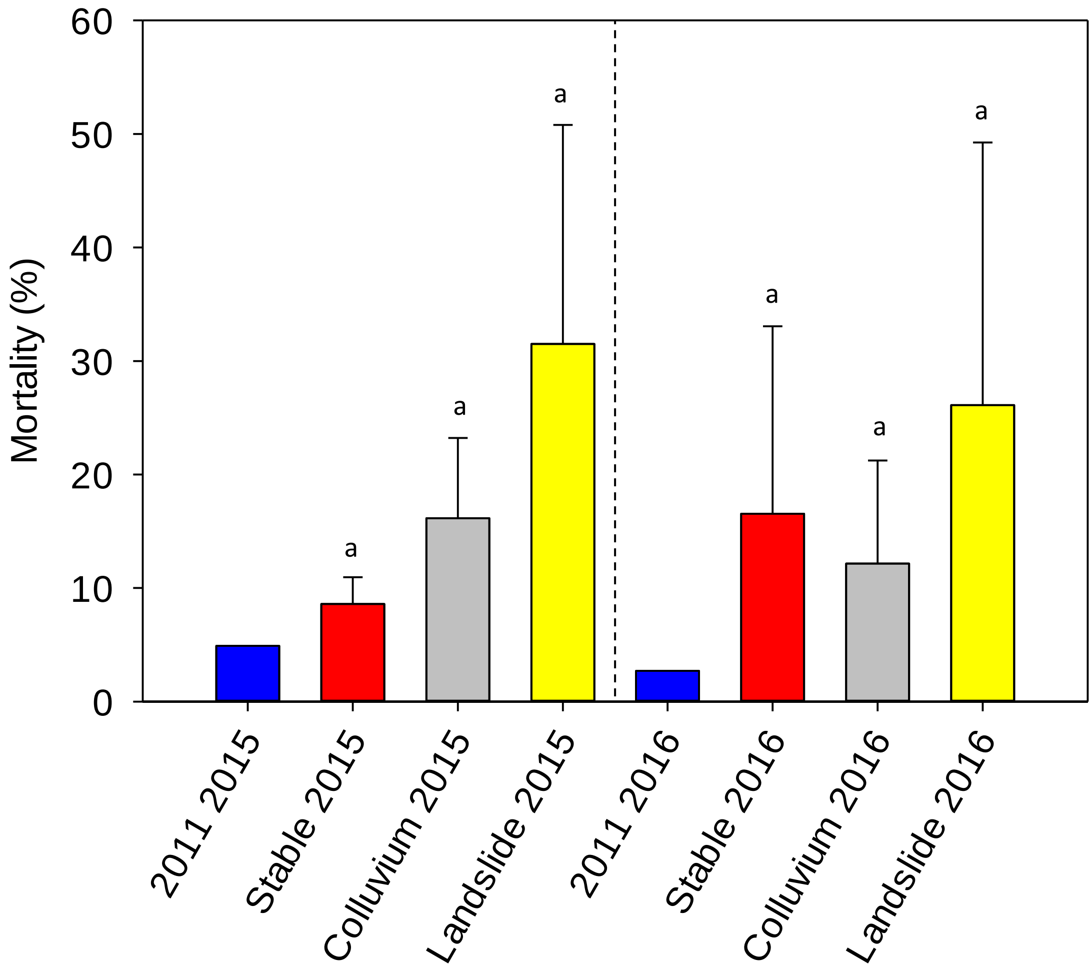

Figure 7 Mortality (%) of mānuka planted in 2011 and 2012 at Lake Tutira on stable interfluves, colluvial slopes and landslide scars measured in 2015 and 2016. Error bars represent one standard deviation. Bars with different letters were significantly different (Student-Newman-Keuls *P*=0.05). The 2011 data were not included in the statistical analysis of mortality at Lake Tutira as they consist of a single data point.

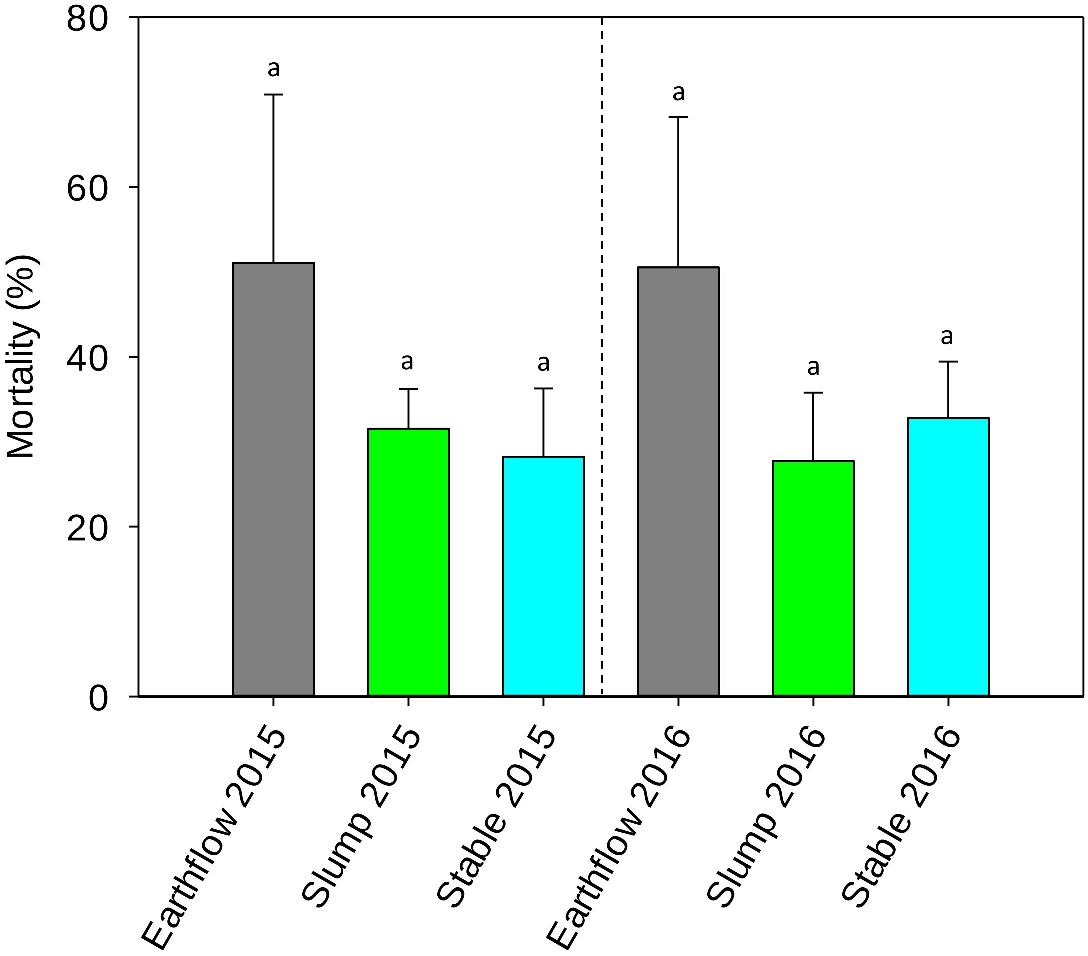

Figure 8 Mortality (%) of mānuka planted in 2013 in earthflow, slump, and stable interfluves at Puketoro Station measured in 2015 and 2016. Error bars are one standard deviation. Bars with different letters were significantly different (Student-Newman-Keuls *P*=0.05).

5.3 Initial planting density

Based on the number of live trees found within the 20 × 20 m permanent sample plots on the different landforms at Lake Tutira, the current plant density ranges between 833 stems ha^{-1} for the poorer landslide scars with thin or no soil cover to 1000 stems ha^{-1} for the stable interfluve ridges/spurs (thicker undisturbed soils), and 1042 stems ha^{-1} for the colluvial slopes with thick but disaggregated and mixed soils. A similar trend can be seen at Puketoro Station where the current planting density is poorer on the more mobile and heavily vegetated (sedges) earthflows at 784 stems ha^{-1} compared with 1125 stems ha^{-1} on the slump terrain, and 1242 stems ha^{-1} on the most stable terrain where soils have remained relatively undisturbed.

The data suggest that at both Lake Tutira and Puketoro Station the current density of surviving (live) plants met the required planting specification, as more seedlings than required were planted. Only the poorer sites such as earthflows at Puketoro (784 stems ha^{-1}) have current plant densities lower than the specified density.

5.4 Growth performance

5.4.1 Tree height

At the time of establishment mānuka seedlings planted at Lake Tutira were ~0.2 m high. As at March 2015, the ~2-m mean height of plants established in 2011 and 2012, with the exception of landslide sites, were not significantly different between the landforms (Fig. 9). Since 2015 there has been a significant increase in the height of mānuka on all the landforms, and there was a clear separation of height between the landforms. Within the 2012 plantings, mānuka were tallest on the colluvial slopes, shorter on the stable interfluves, and shortest on the landslide scars. The 2011 mānuka plantings were shorter still (Fig. 9).

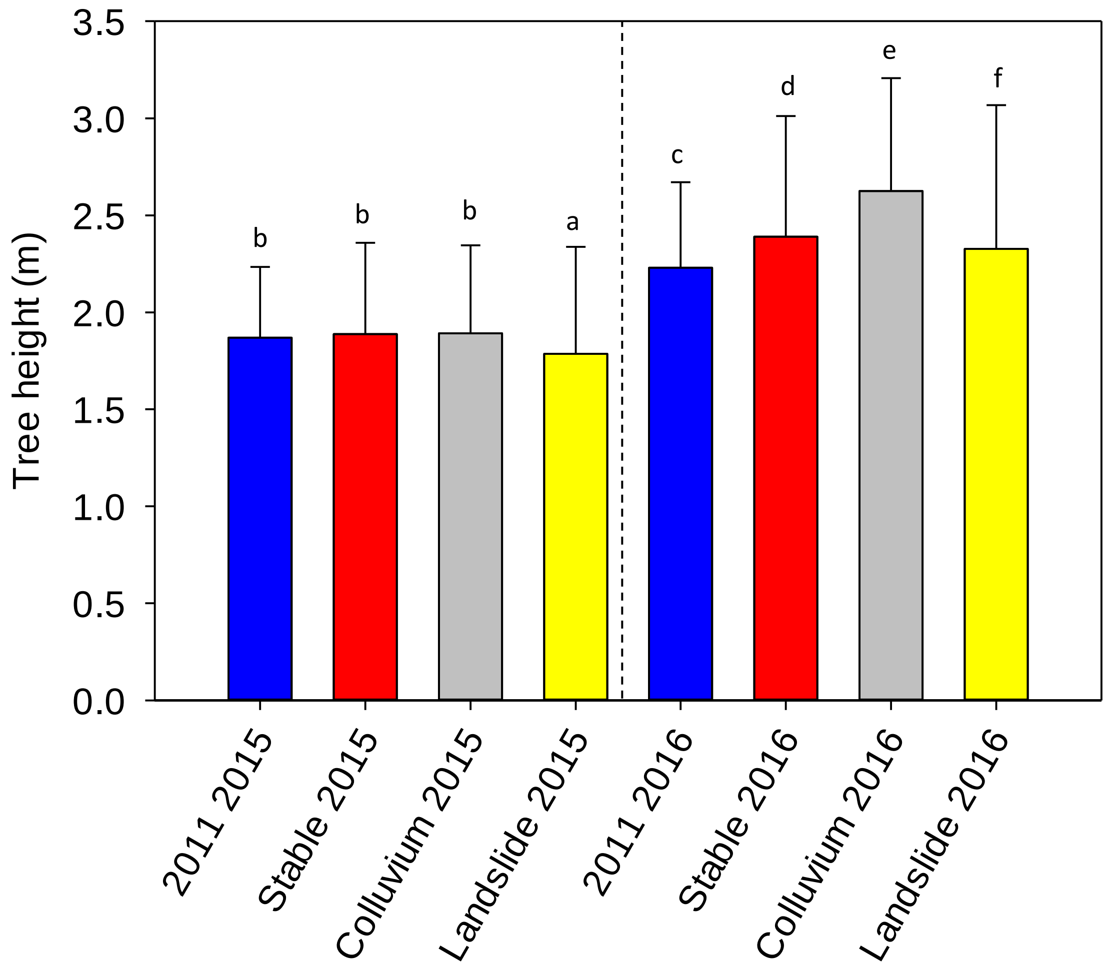

Figure 9 Mean height of mānuka plantings at Lake Tutira. The 2011 plantings(blue) were measured in 2015 and 2016. The stable (red), colluvium (grey) and landslide (yellow) landforms, planted in 2012, were measured in 2015 and 2016. Bars represent standard deviation, bars with different letters were significantly different *(P*=0.05).

At Puketoro Station, the 2013 plantings had by 2015 reached a mean tree height of ~1 m and there were no significant differences in tree height between the landforms. Similarly, by 2016, there were no significant differences in the mean tree height between landforms, and surprisingly there had not been a significant increase in mean tree height since 2015 (Fig. 10).

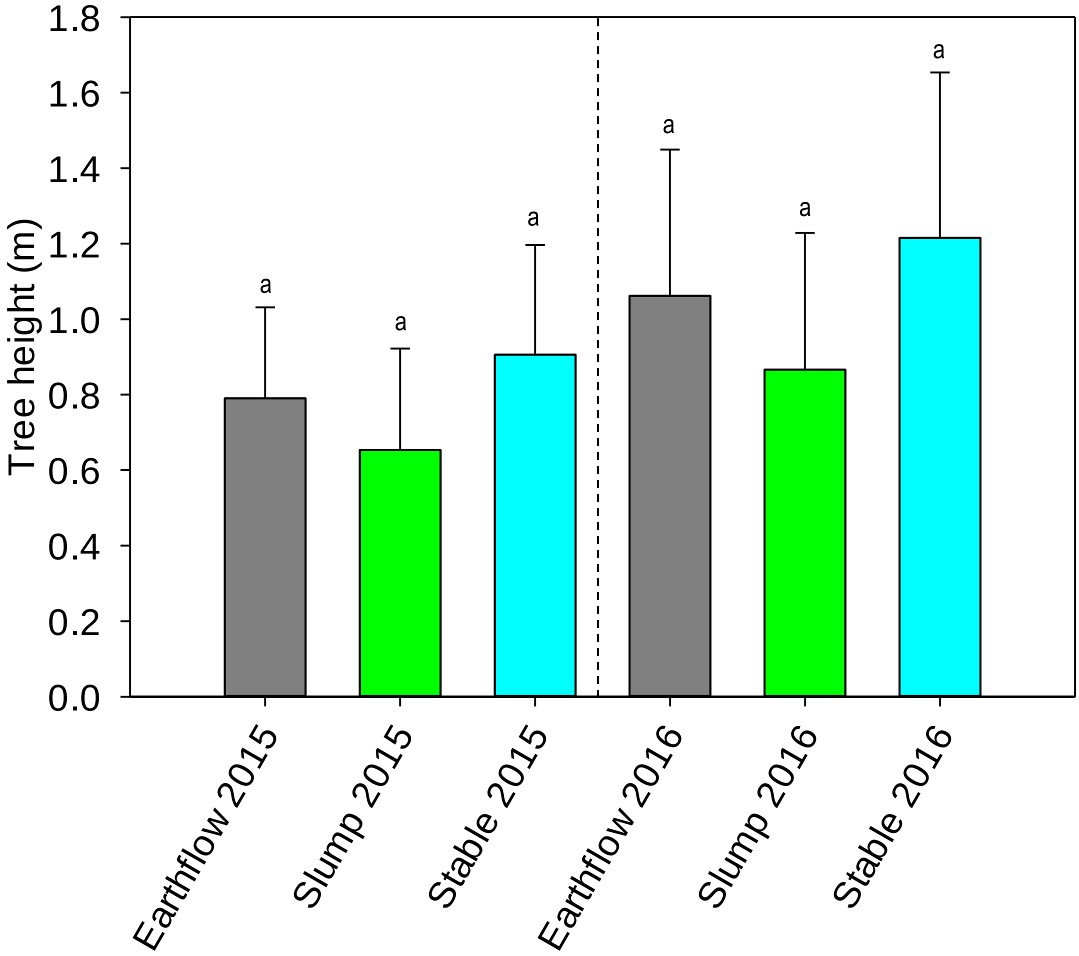

Figure 10 Mean tree height of 2013 mānuka plantings on the three landforms at Puketoro Station measured in 2015 and 2016. Bars represent standard deviation, bars with different letters were significantly different *(P*=0.05).

5.4.2 Root collar diameter (measured at ground level)

At the time of establishment the mānuka seedlings planted at Lake Tutira had a collar diameter of ~3–4 mm (James Powrie, pers. comm.). By 2015, the root collar diameter of the 2012 plantings established on the colluvial slopes and landslide scar (~18 mm) were not significantly different from each other but were both significantly different to that of mānuka established on the stable interfluves (~20 mm), and to the older 2011 plantings with a mean root collar diameter of 40 mm (Fig. 11). Between 2015 and 2016, there was a significant increase in root collar diameter across all landforms, and in both years the 2011 site remained the site with the greatest mean root collar diameter. In 2016, the root collar diameter of mānuka established on the colluvial slopes was now greater than that of mānuka established on the stable interfluves, and for both these landforms the root collar diameter was significantly greater than that of mānuka established on the landslide scars. The rate of increase in root collar diameter for mānuka established on landslide scars is significantly less than for mānuka established on both the colluvial slopes and stable interfluves.

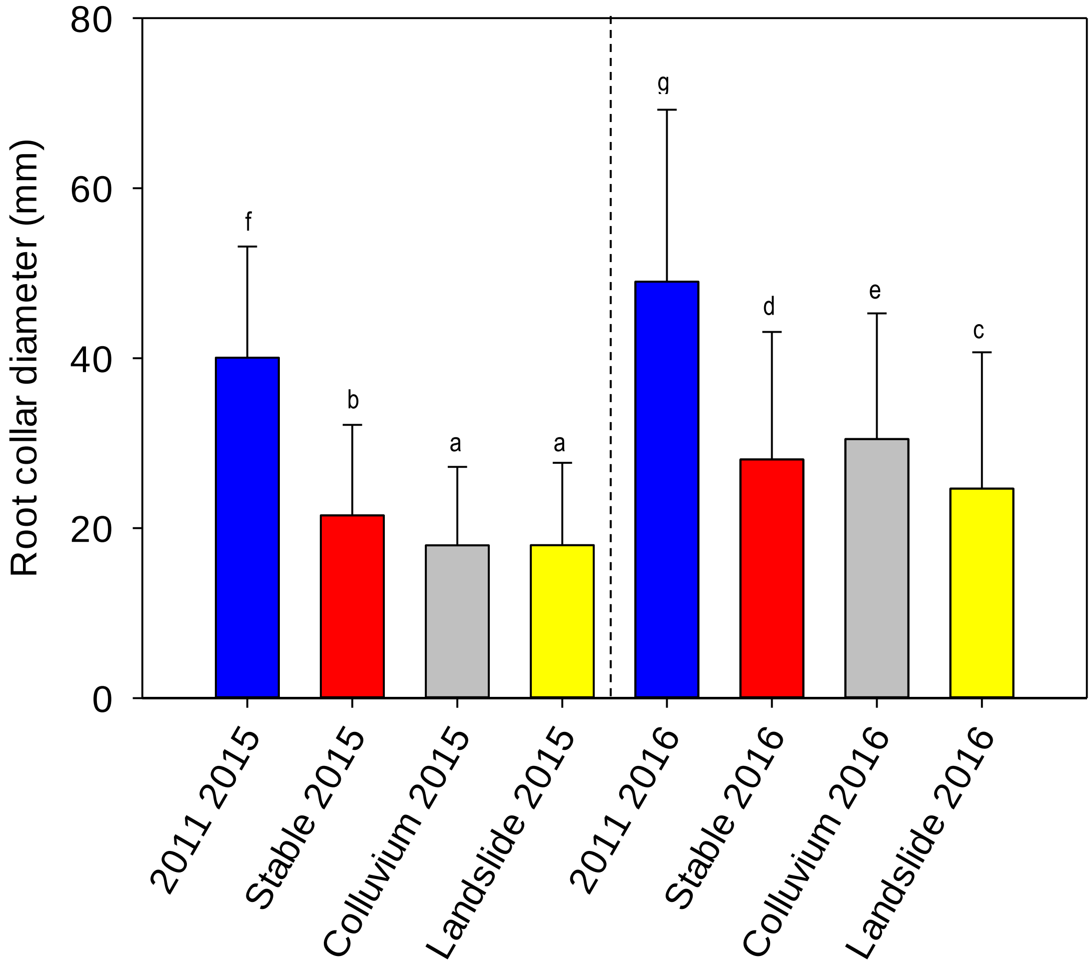

Figure 11 Mean root collar diameter of mānuka plantings at Lake Tutira. The 2011 plantings(blue) were measured in 2015 and 2016. The stable (red), colluvium (grey) and landslide (yellow) landforms, planted in 2012, were measured in 2015 and 2016. Bars represent standard deviation, bars with different letters were significantly different *(P*=0.05).

At Puketoro Station, the mean root collar diameter across all sites 2 years after establishment was just 4 mm (Fig. 12) but was nonetheless significantly greater on the stable interfluves compared to the earthflow and slump landforms, which were not significantly different from each other. Between 2015 and 2016, there was a significant increase in root collar diameter across all landforms, and as was the case in 2015, the root collar diameter of mānuka established on the stable interfluves was significantly greater than that of mānuka established on both earthflow and slump landforms which were not significantly different from each other.

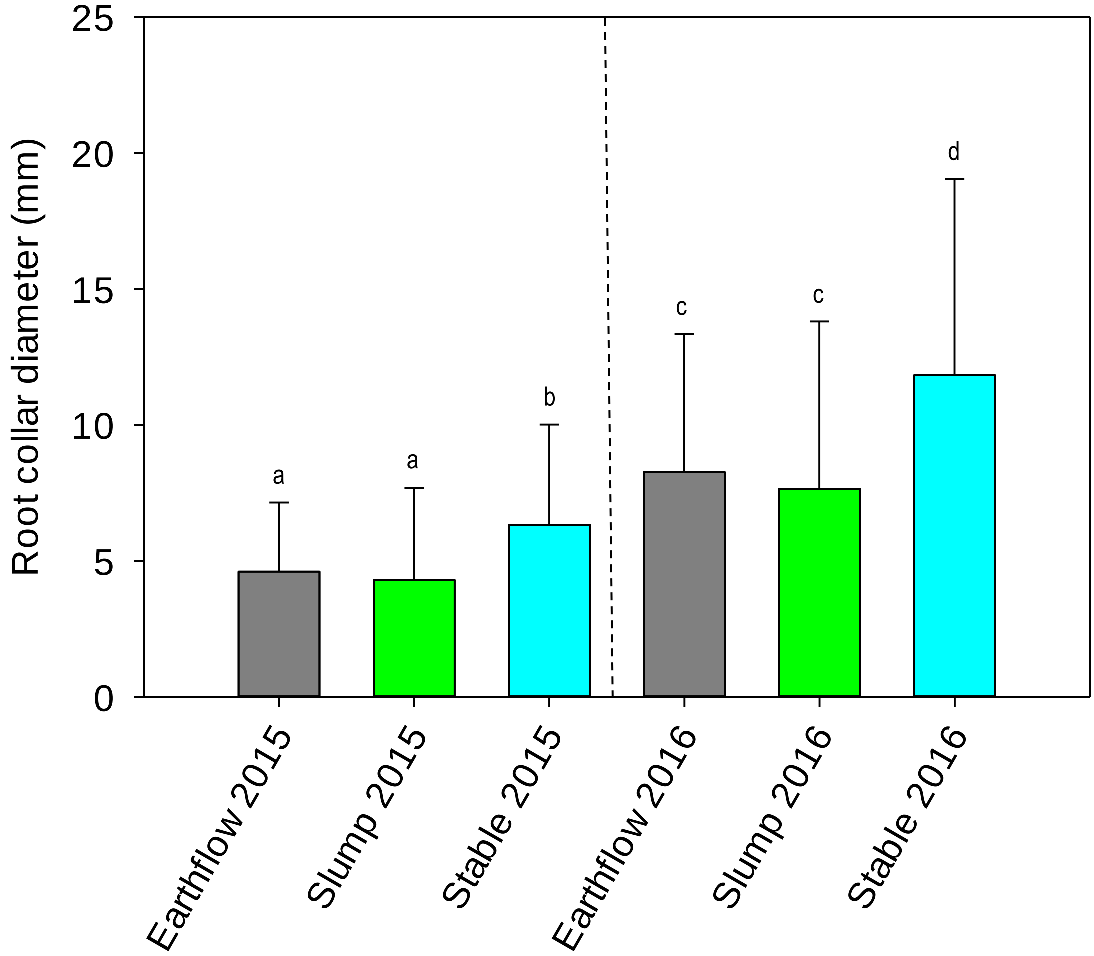

Figure 12 Mean root collar diameter of 2013 plantings on the three landforms at Puketoro Station measured in 2015 and 2016. Error bars represent standard deviation, bars with different letters were significantly different (*P*=0.05).

5.4.3 Diameter at breast height (measured at 1.4 m above ground level)

In 2015, at Lake Tutira, the mean diameter at breast height (~4 mm) was not significantly different across any of the landforms planted in 2012 or to plantings established in 2011 (Fig. 13). Between 2015 and 2016, there was a significant increase in mānuka DBH across all the landforms. By 2016, there was clear separation in DBH measurements between each of the landforms. The smallest increase in mean DBH was for mānuka planted in 2011. For the 2012 plantings, the increase in DBH was greatest for mānuka on colluvial slopes, less for mānuka on landslide scars, and least for mānuka on stable interfluve ridges and spurs.

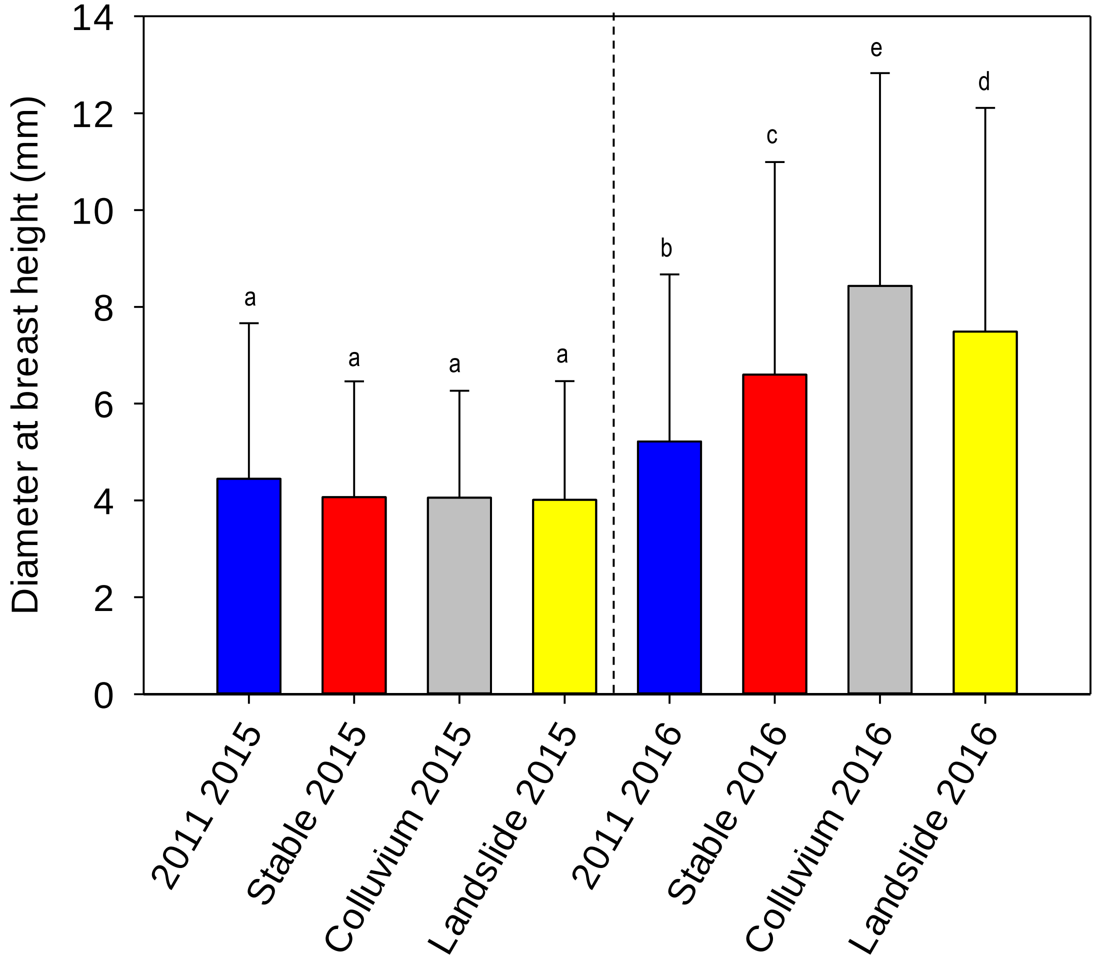

Figure 13 Mean diameter at breast height of mānuka plantings at Lake Tutira. The 2011 plantings(blue) were measured in 2015 and 2016. The stable (red), colluvium (grey) and landslide (yellow) landforms, planted in 2012, were measured in 2015 and 2016. Bars represent standard deviation, bars with different letters were significantly different *(P*=0.05).

At Puketoro Station, none of the 2013 mānuka plantings established on earthflows reached DBH height, while on the slump and stable interfluves the mean diameter at breast height was 2 mm, and was not significantly different between these two landforms (Fig. 14). By 2016, as for the Lake Tutira site, there was a significant increase in DBH across all the landforms but here it was significantly greater for plantings on the stable interfluves, relative to plantings on earthflow and slump landforms, which were not significantly different from each other.

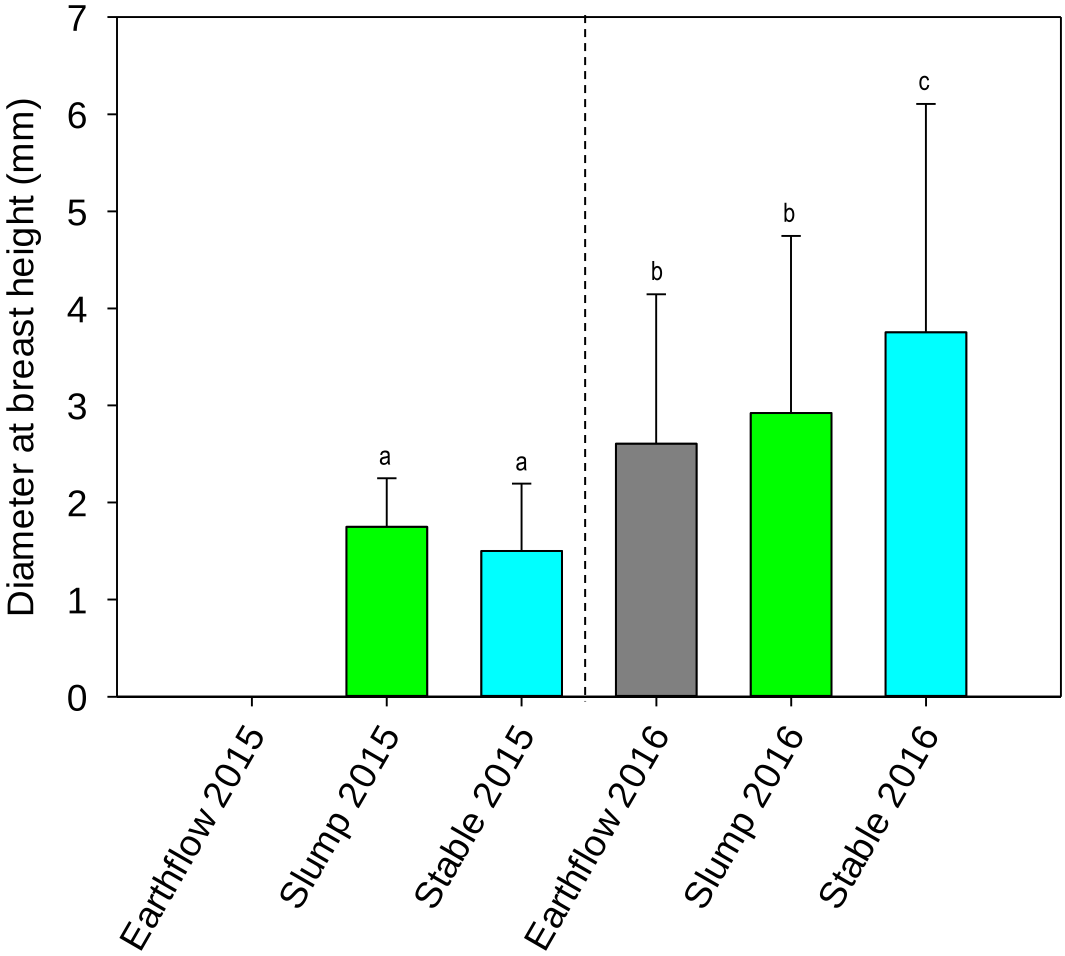

Figure 14 Mean diameter at breast height of 2013 mānuka plantings on the three landforms at Puketoro Station measured in 2015 and 2016. Error bars represent standard deviation, bars with different letters were significantly different (*P*=0.05). Note: as at 2015, plants established on earthflows had not reached dbh height.

5.4.4 Canopy diameter

As at 2015, the mean canopy diameter of the 2011 and 2012 mānuka plantings at Lake Tutira (~1.1 m and ~1.2 m respectively), was not significantly different. Additionally, the mean canopy diameter of the 2012 plantings established on stable interfluves, colluvial slopes, and landslide scars was not significantly different (Fig. 15). By 2016, the 2011 plantings and the 2012 plantings established on stable interfluves and colluvial slopes, though not significantly different from each other, had a significantly wider canopy diameter than did plantings established on landslide scars (Fig. 15).

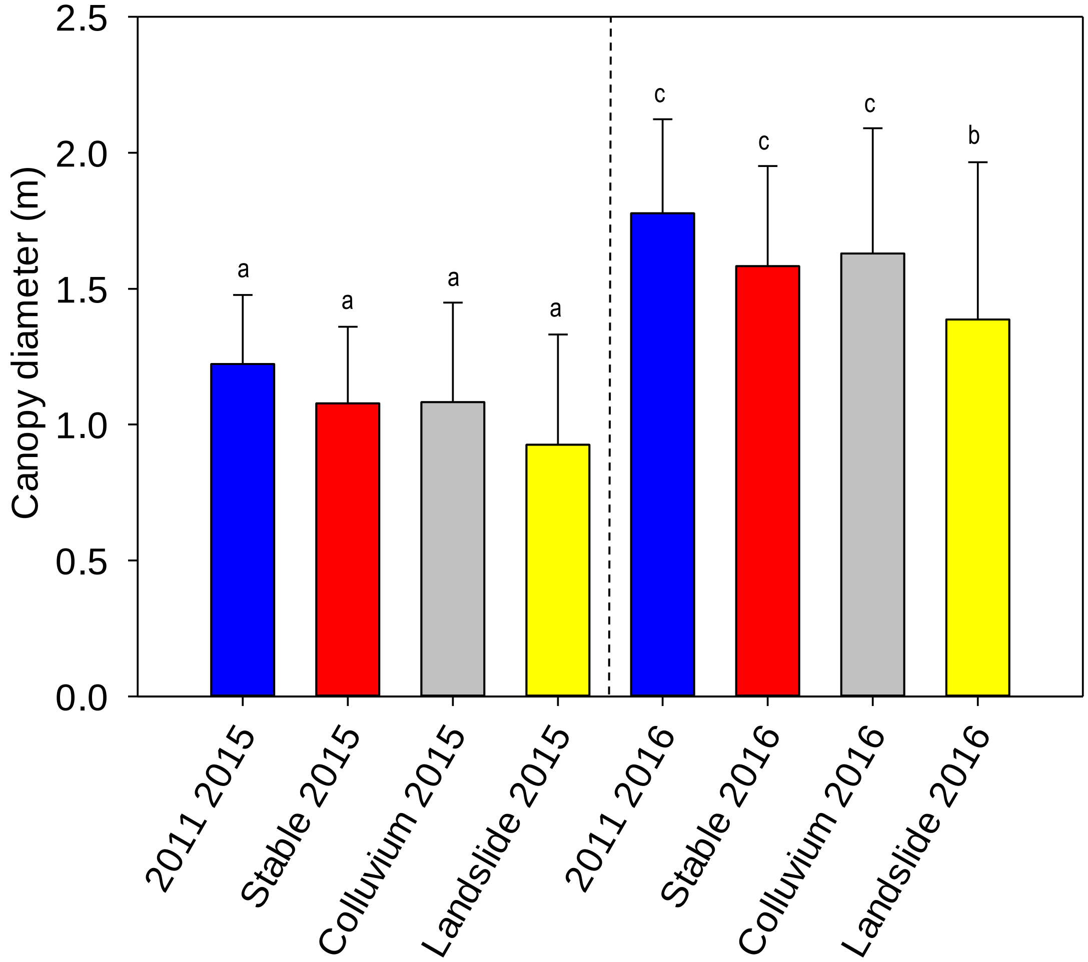

Figure 15 Canopy diameter of mānuka planted at Lake Tutira. The 2011 plantings(blue) were measured in 2015 and 2016. The stable (red), colluvium (grey) and landslide (yellow) landforms, planted in 2012, were measured in 2015 and 2016. Bars represent standard deviation, bars with different letters were significantly different *(P*=0.05).

At Puketoro Station, the mean canopy diameter of mānuka plantings in 2015 was ~0.5 m, and at this time there were no significant differences in canopy development between plantings on any of the landforms (Fig. 16). By 2016, the canopy diameter had not increased significantly on any of the landforms since 2015, and there were no significant differences in the canopy diameter of plantings across these landforms.

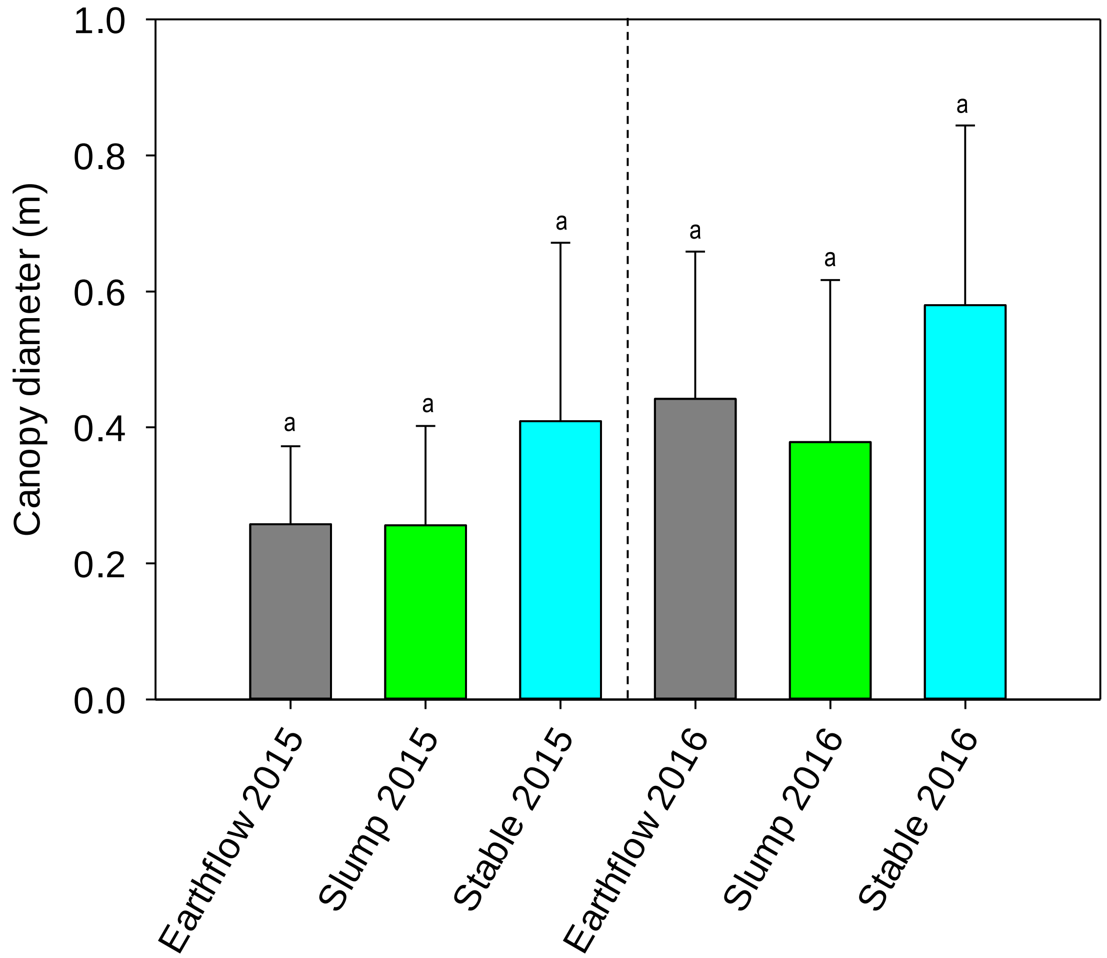

Figure 16 Canopy diameter of 2013 mānuka plantings on the three landforms at Puketoro Station measured in 2015 and 2016. Error bars bar represent standard deviation. Error bars represent standard deviation, bars with different letters were significantly different (*P*=0.05).

5.4.5 Regression analyses

For the Lake Tutira data, the linear regression analysis fitting RCD and tree height had similar r^2 and r (square root of r^2 in Table 3) for all of the landforms, suggesting that the relationship between RCD and tree height was unaffected by landform (Fig. 17; Table 3). The larger root collar diameter but stunted stature of the 2011 plantings (r^2=0.37), suggest that mānuka within the area of this permanent sample plot were slower to establish because of the higher altitude and greater exposure to climatic influences.

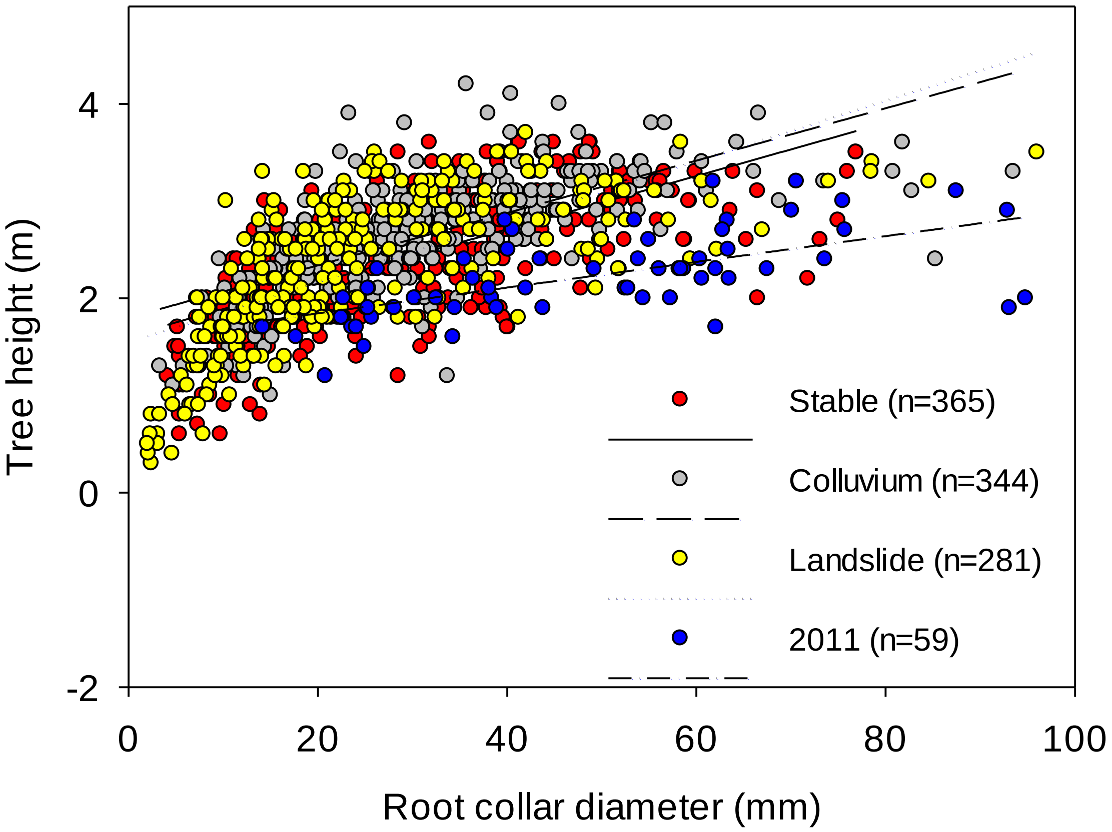

Figure 17 Linear regression of root collar diameter against tree height for mānuka planted at Lake Tutira in 2011 and 2012 measured in 2016, with respect to landform. Numbers in parentheses are the numbers of mānuka stems measured. Regression statistics (slope, intercept, r², standard error of estimate, respectively), are given in Table 3.

Table 3 Regression statistics for root collar diameter against tree height for mānuka planted at Lake Tutira in 2011 and 2012, with respect to landform

Age and landform	r²	*P*	Slope	Intercept	SEE*
2011					
Stable	**0.37**	**<0.001**	**0.013**	**1.58**	**0.35**
2012					
Stable	0.43	<0.001	0.027	1.61	0.47
Colluvial slope	0.47	<0.001	0.027	1.80	0.43
Landslide scar	0.48	<0.001	0.031	1.53	0.55

*Standard error of the estimate

For the Puketoro Station data, the similarity in the linear regression analysis fitting RCD and tree height for plantings across the different landforms, with r² ranging between 0.69 and 0.75, likely indicates that this relationship is independent of landform type (Fig. 18; Table 4).

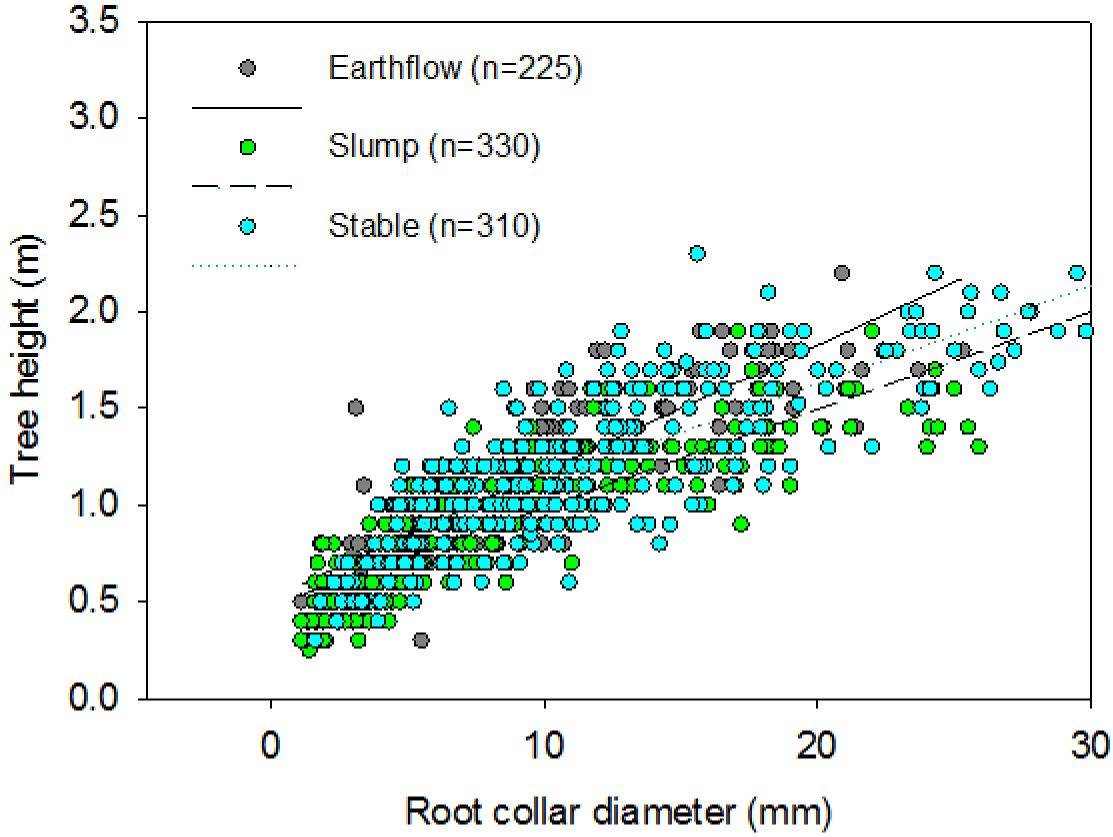

Figure 18 Linear regression of root collar diameter against tree height for mānuka planted in 2013 at Puketoro Station measured in 2016, with respect to landform. Numbers in parentheses are the numbers of mānuka stems measured. Regression statistics (slope, intercept, r^2, standard error of estimate, respectively) are given in Table 4.

Table 4 Regression statistics for root collar diameter against tree height for mānuka planted at Puketoro Station in 2013, with respect to landform

Landform	r^2	*P*	Slope	Intercept	SEE*
Earthflow	0.75	<0.001	0.065	0.52	0.19
Slump	0.75	<0.001	0.051	0.48	0.18
Stable	0.69	<0.001	0.051	0.62	0.24

*Standard error of the estimate

6 Root spread

The mean maximum root spread of the lateral roots of mānuka planted in 2011 at Lake Tutira was ~3.5 m. There were no significant differences in root spread between the 2011 plantings, and the 2012 plantings on stable interfluves and colluvial slopes (Fig. 19). While the root spread of the 2012 mānuka plantings on landslide scars (~1 m) are not significantly different from the same age plantings on stable interfluves and colluvial slopes, their root systems were nonetheless considerably more compact than those of the 2011 plantings (Fig. 19).

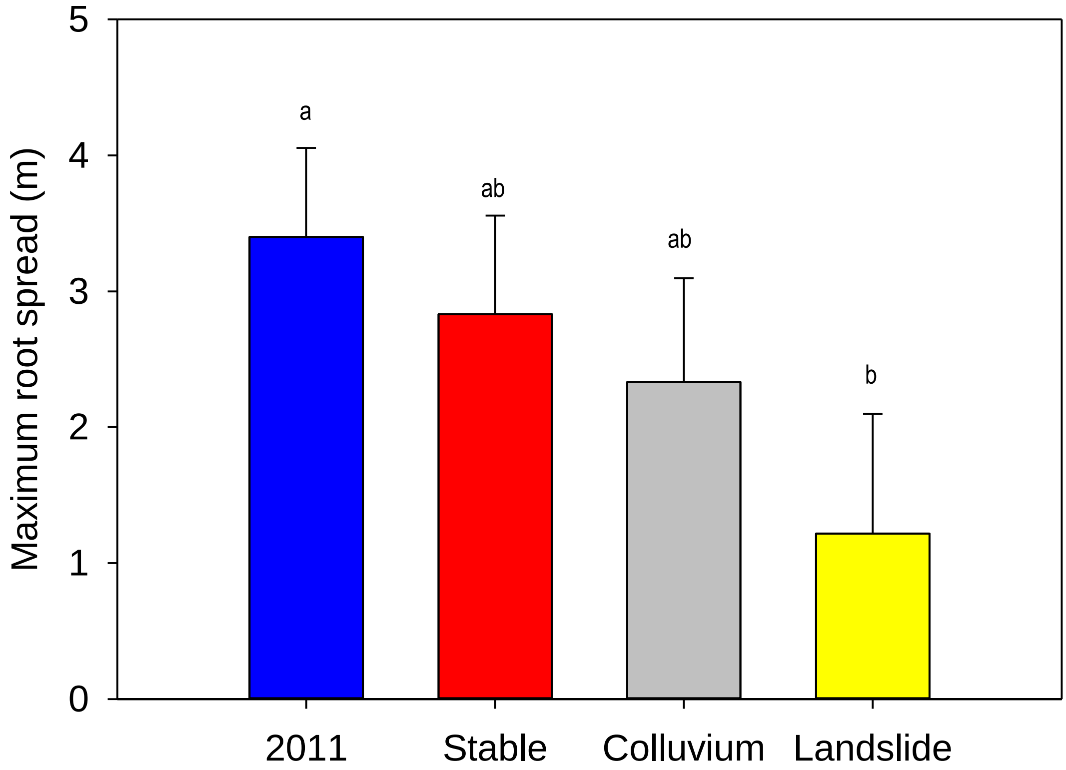

Figure 19 Mean maximum root spread of mānuka planted in 2011 at Lake Tutira (stable interfluve), and for 2012 plantings established on stable, colluvium and landslides when measured in 2016. Error bars represent standard deviation; bars with different letters were significantly different (*P*=0.05).

At Puketoro, the mean maximum root spread of the 2013 plantings was <0.6 m and was not significantly different across the three landforms present at this location (Fig. 20).

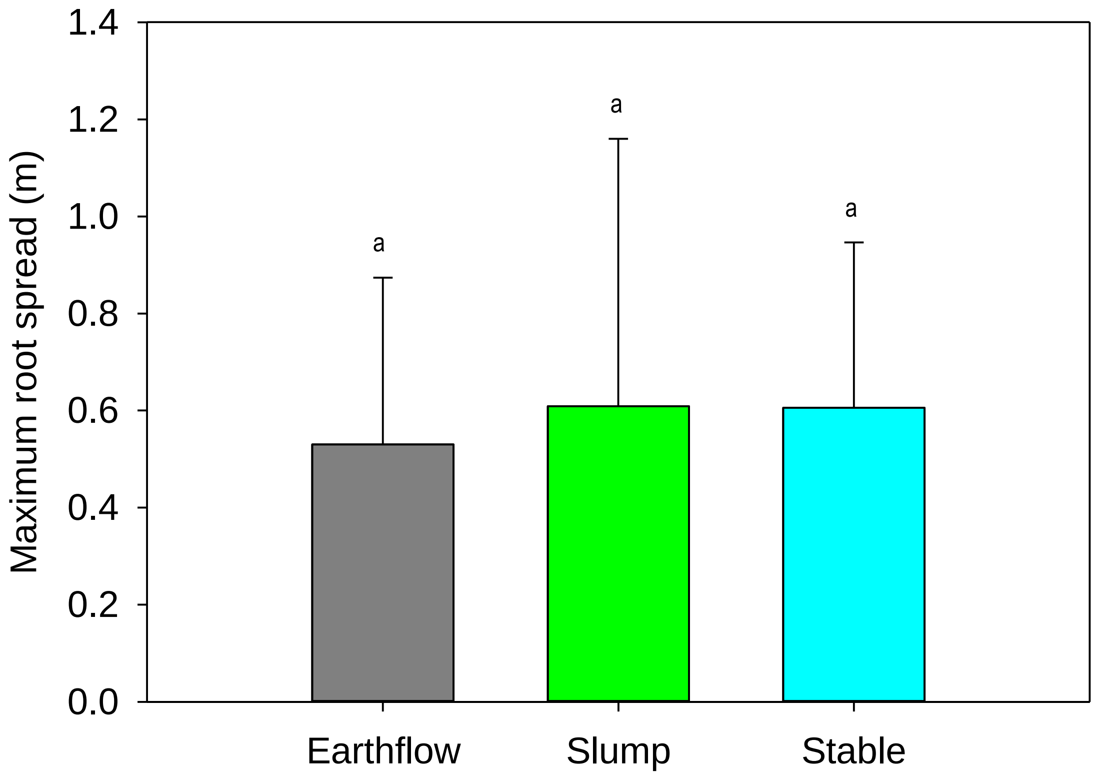

Figure 20 Mean maximum root spread of 2013 mānuka plantings established on different landforms present at Puketoro Station when measured in 2016. Error bars bar represent standard deviation. Error bars represent standard deviation; bars with different letters were significantly different (*P*=0.05).

7 Root depth

The mean maximum rooting depth of the oldest (2011) mānuka plantings at Lake Tutira is ~ 1.1 m. There were no significant differences in rooting depth between the 2011 plantings and the 2012 plantings on the stable interfluves or between each of the landforms planted in 2012 (Fig. 21). Additionally, the rooting depths of mānuka on colluvial slopes and landslide scars, though not significantly different from each other (~0.5 m), are significantly shallower than for the 2011 plantings.

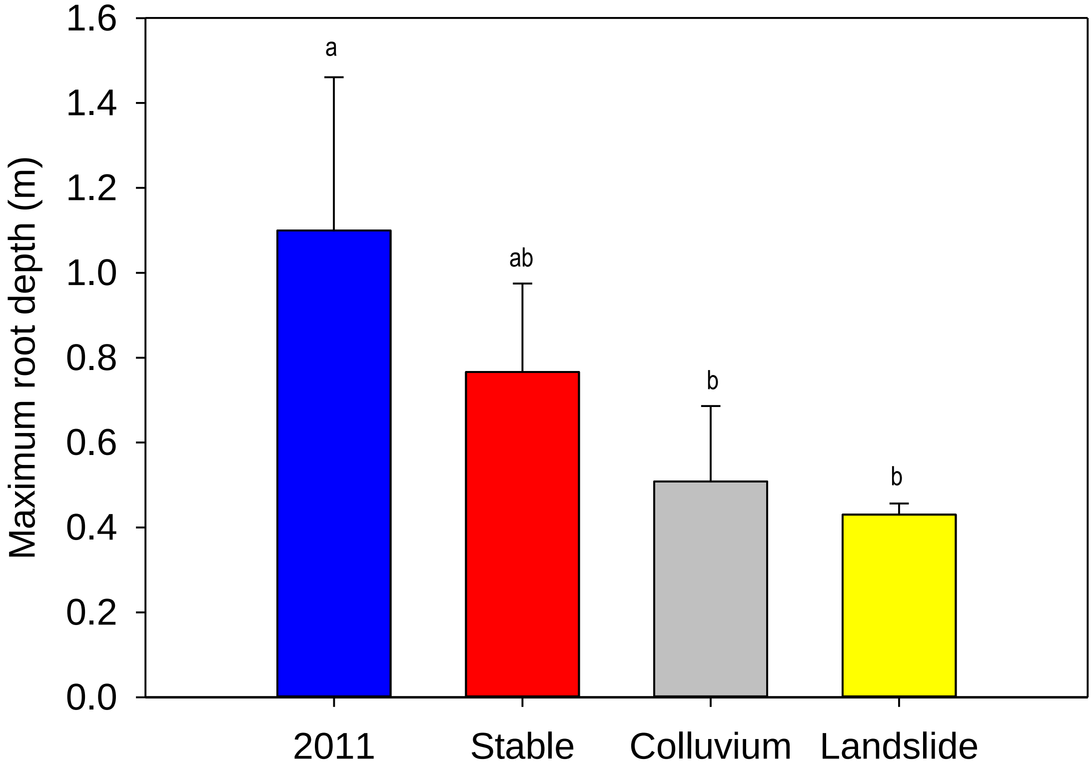

Figure 21 Mean maximum root depth of mānuka planted at Lake Tutira in 2011 (stable interfluves) and of 2012 plantings on stable, colluvium and landslides when measured in 2016. Error bars represent standard deviation; bars with different letters were significantly different (*P*=0.05).

The mean maximum rooting depth of the 2013 mānuka plantings at Puketoro is <0.23 m and was not significantly different across the three landforms present at this location (Fig. 22).

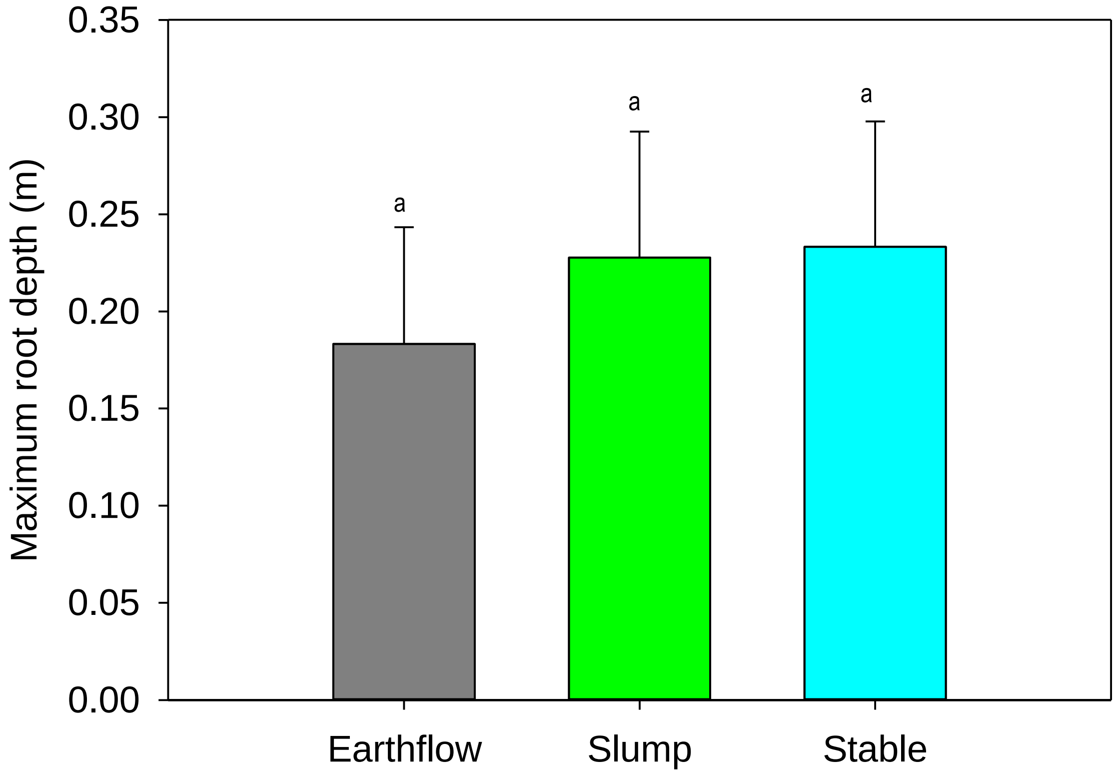

Figure 22 Mean maximum root depth of 2013 mānuka plantings on the three landforms present at Puketoro Station when measured in 2016. Error bars represent standard deviation; bars with different letters were significantly different (*P*=0.05).

8 Above-ground biomass

The above-ground biomass of mānuka plantings at Lake Tutira (Fig. 23) was not significantly different between landforms or between the 2011 and 2012 plantings and comprised >80% of total plant biomass. Similarly, at Puketoro Station (Fig. 24) the above-ground biomass of mānuka was not significantly different between landforms and for these younger plantings comprising >80% of total plant biomass.

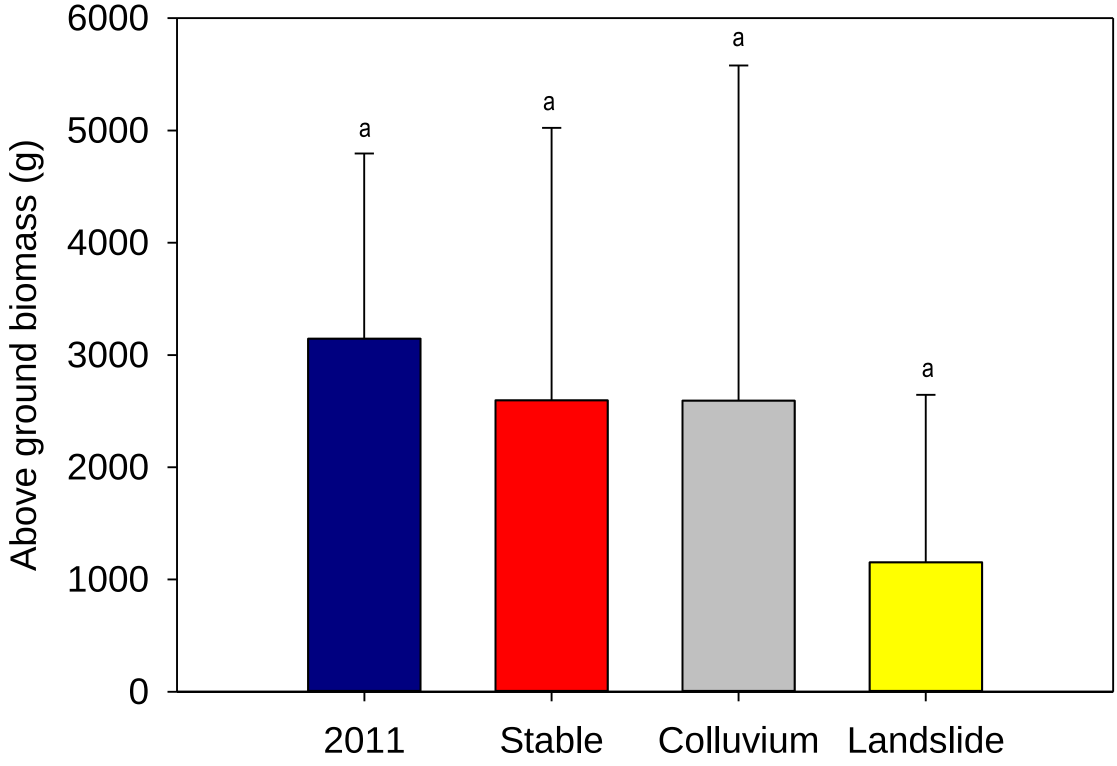

Figure 23 Mean above-ground biomass of mānuka at Lake Tutira planted in 2011 (stable site) and of 2012 plantings on stable, colluvium and landslides when measured in 2016. Error bars represent standard deviation; bars with different letters were significantly different (*P*=0.05).

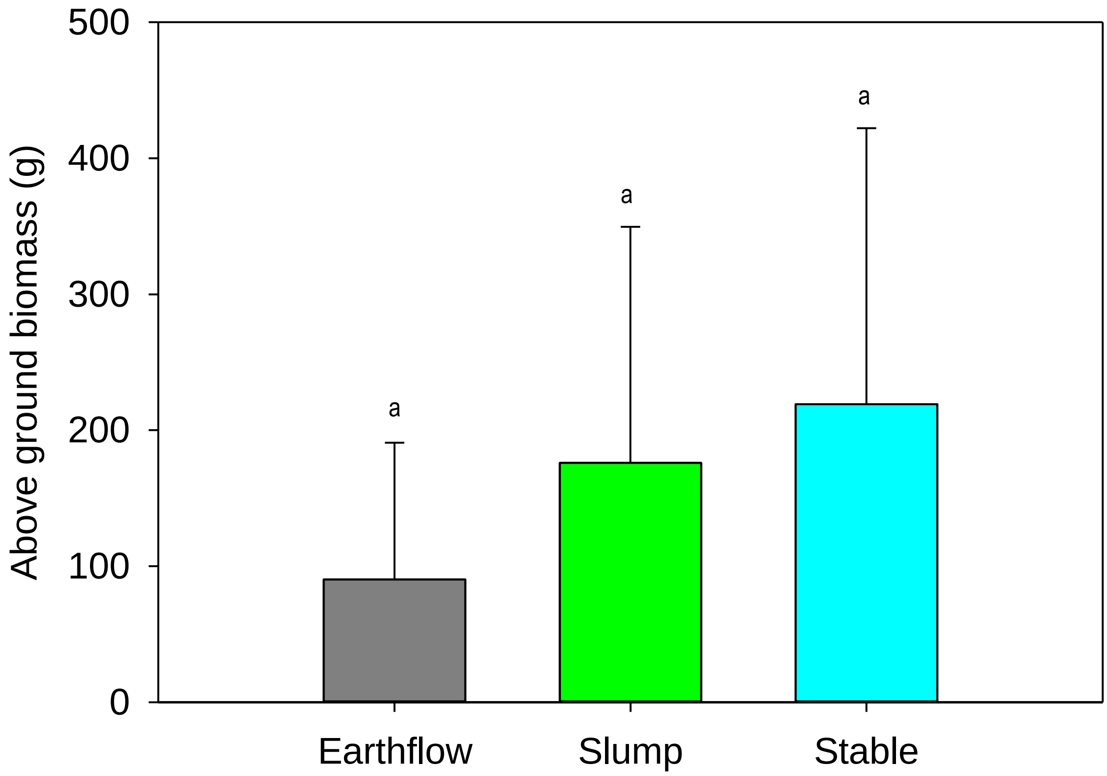

Figure 24 Mean above ground biomass of mānuka planted in 2013 on the three landforms at Puketoro Station when measured in 2016. Error bars represent standard deviation; bars with different letters were significantly different (*P*=0.05).

9 Below-ground biomass

At Lake Tutira, and irrespective of the age of mānuka plantings, there were no significant differences in total below-ground biomass between any of the landforms (Fig. 25), with root biomass comprising <20% of total plant biomass. Similarly, because of the high variability in the total below-ground biomass of the 2013 mānuka plantings at Puketoro Station, it was not significantly different across the three landforms (Fig. 26), and the root biomass of these younger plantings comprised <20% of total plant biomass.

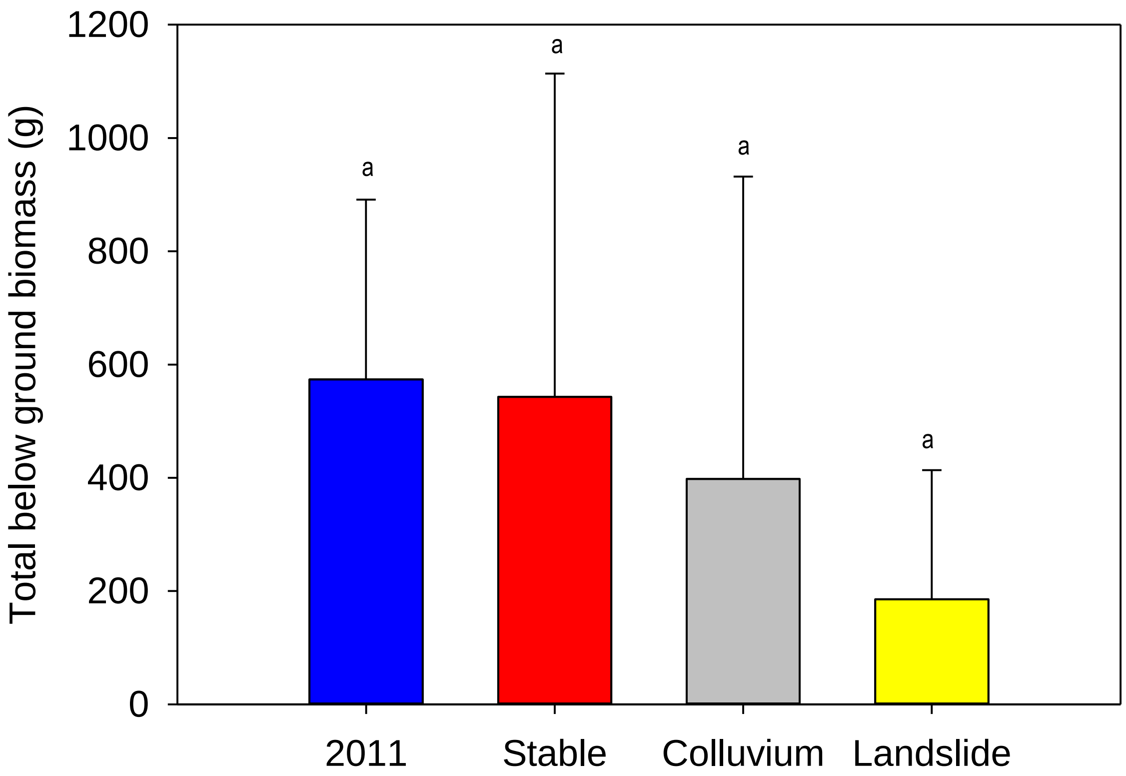

Figure 25 Total below ground biomass of mānuka planted at Lake Tutira in 2011 (stable interfluves) and of 2012 plantings on the stable, colluvium and landslides when measured in 2016. Error bars represent standard deviation; bars with different letters were significantly different (*P*=0.05).

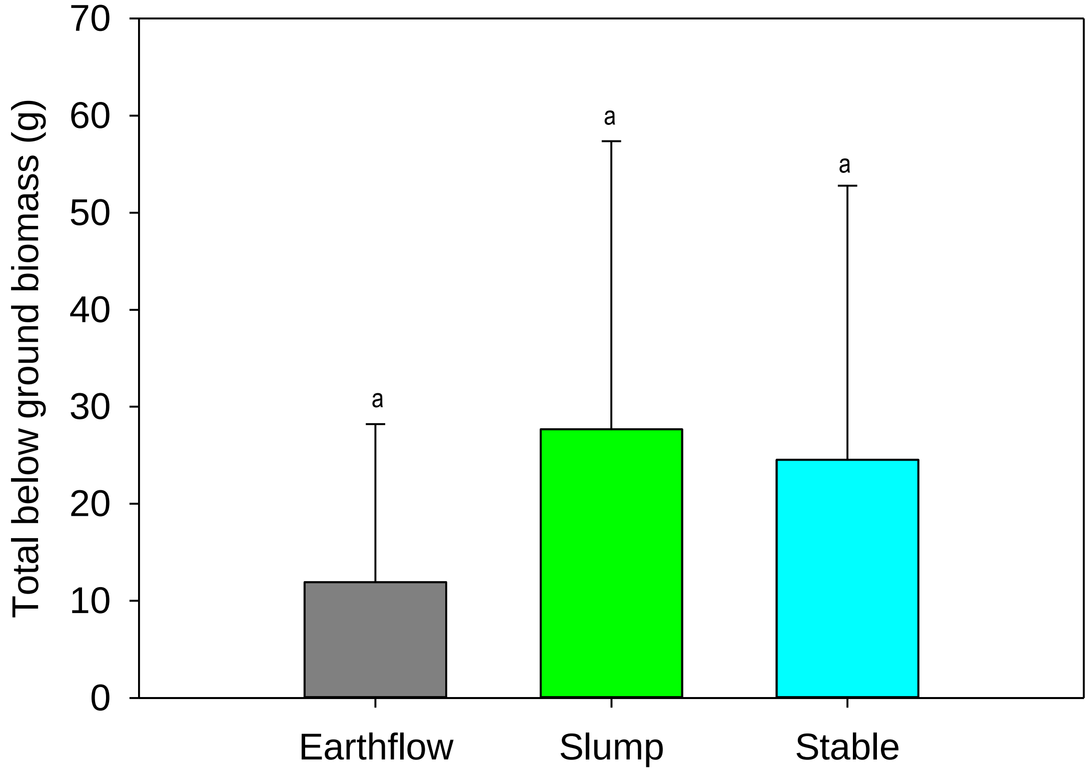

Figure 26 Total below-ground biomass of 2013 mānuka plantings on the three landforms at Puketoro Station when measured in 2016. Error bars bar represent standard deviation. Error bars represent standard deviation; bars with different letters were significantly different (*P*=0.05).

10 Root: shoot ratio

The root: shoot ratio of mānuka plantings at Lake Tutira (Fig. 27) was not significantly different between landforms or between the 2011 and 2012 plantings. Similarly, at Puketoro Station (Fig. 28) the root: shoot ratio of mānuka was not significantly different between landforms.

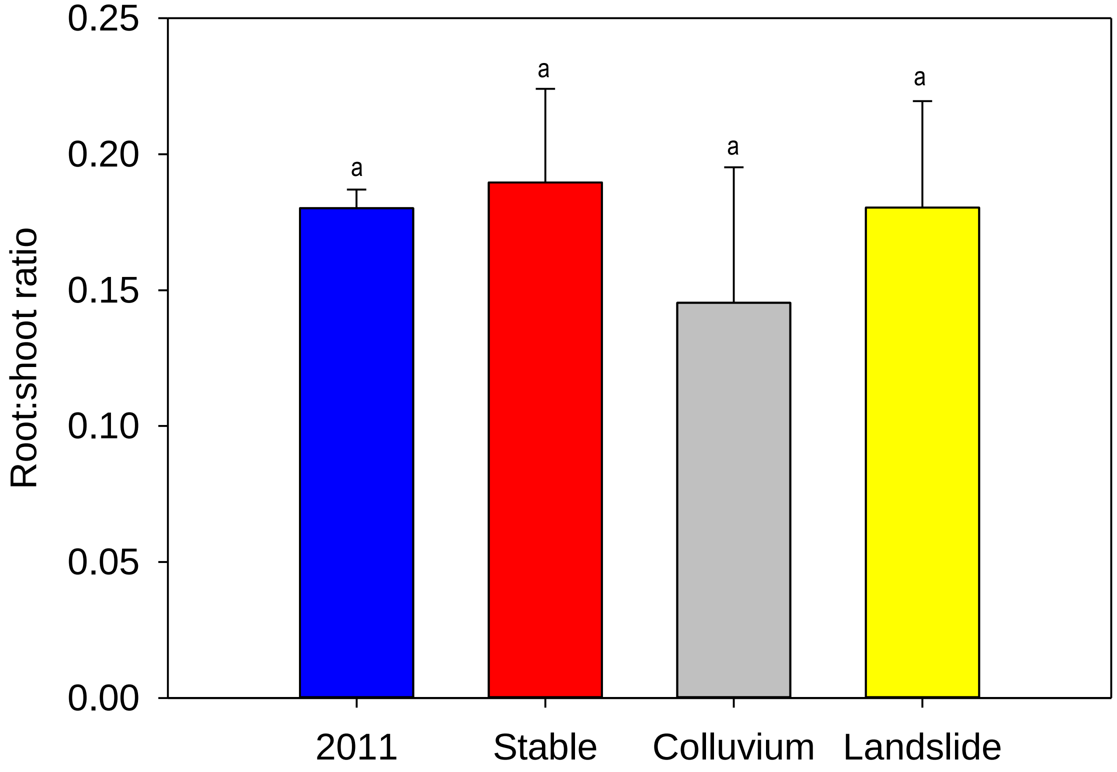

Figure 27 Root: shoot ratio of mānuka planted at Lake Tutira in 2011 (stable interfluves) and of 2012 plantings on stable, colluvium and landslides when measured in 2016. Error bars represent standard deviation; bars with different letters were significantly different (*P*=0.05).

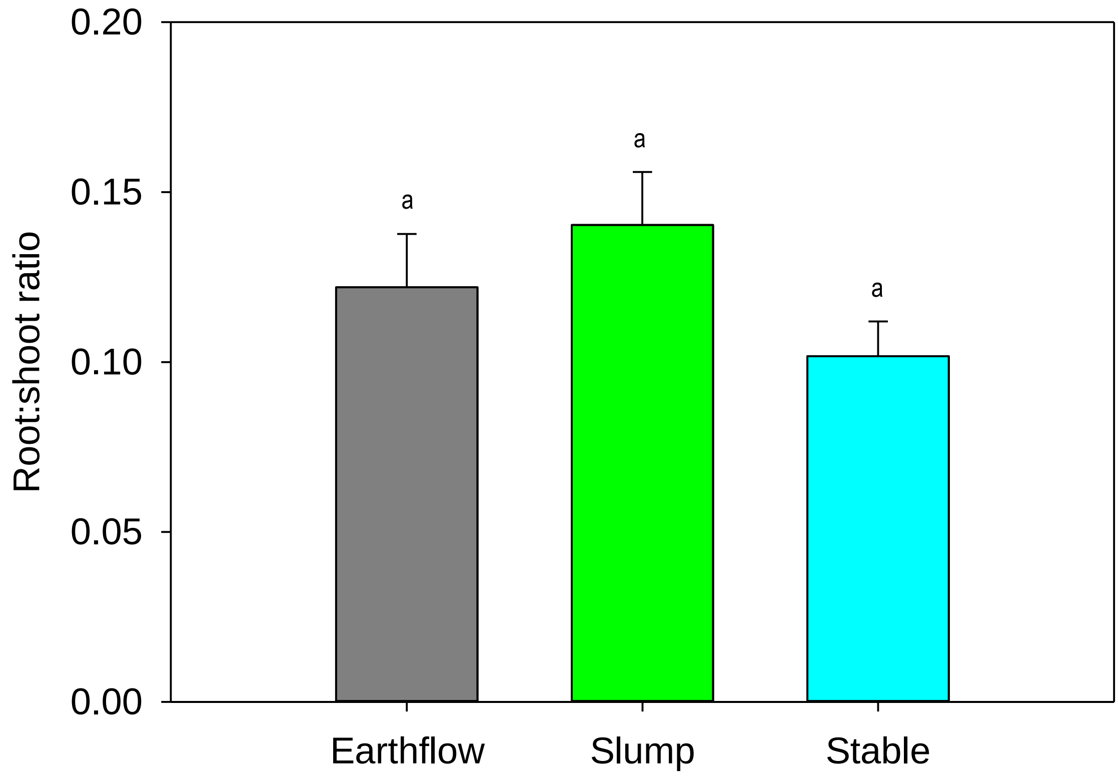

Figure 28 Root: shoot ratio of 2013 mānuka plantings on the three landforms at Puketoro Station when measured in 2016. Error bars bar represent standard deviation. Error bars represent standard deviation; bars with different letters were significantly different (*P*=0.05).

11 Mean total plant and total stand biomass by age class and landform

Mean total plant biomass of mānuka plantings at Lake Tutira and Puketoro Station were not significantly different between the landforms present at these respective sites. Similarly, at Lake Tutira there was no significant difference in mean total plant biomass between the 2011 and 2012 plantings.

As at 2016, differences in total stand biomass between the 2011 and 2012 plantings at Lake Tutira were not significantly different or between the 3 landforms planted in 2012 and ranged between 1115 kg/ha and 3719 kg/ha (Table 5). There were also no significant differences between the total stand biomass at the Puketoro Station site, where biomass ranged between 80 and 244 kg/ha (Table 6).

Table 5 Mean total plant and total stand biomass by age class and landform at Lake Tutira

Landform type and age of plantings	Stable interfluves 2011 plantings	Stable interfluves 2012 plantings	Colluvial slopes 2012 plantings	Landslide scar 2012 plantings
Area (ha)	0.96	22.3	4.5	11.5
Density (spha)	1000	1000	1042	833
Mean total plant biomass (g)	3719 (1967)[a]	3139 (2997)[a]	2990 (3517)[a]	1339 (1720)[a]
Total stand biomass (kg/ha)	3719 (1967)[a]	3139 (2997)[a]	3115 (3665)[a]	1115 (1433)[a]
Total stand biomass (t C/ha)	1.86 (0.98)[a]	1.57 (1.50)[a]	1.56 (1.83)[a]	0.56 (0.72)[a]
Total stand biomass (t CO_2/ha)	3.07 (1.62)[a]	2.59 (2.47)[a]	2.57 (3.02)[a]	0.92 (1.18)[a]
Annual rate of biomass production (kg/ha/yr)	744 (393)[a]	785 (749)[a]	779 (916)[a]	279 (358)[a]
Annual rate of biomass C production (t CO2/ha/yr)	0.37 (0.20)[a]	0.39 (0.37)[a]	0.39 (0.46)[a]	0.14 (0.18)[a]
Annual rate of biomass CO_2 production (t CO2/ha/yr)	0.61 (0.32)[a]	0.65 (0.62)[a]	0.64 (0.76)[a]	0.23 (0.30)[a]

Table 6 Mean total plant and total stand biomass by age class and landform at Puketoro Station

Landform type and age of plantings	Stable interfluves 2013 plantings	Slump 2013 plantings	Earthflow 2013 plantings
Area (ha)	20.6	64.2	34.4
Density (spha)	1242	1125	784
Mean total plant biomass(g)	102 (115)[a]	204 (203)[a]	102 (115)[a]
Total stand biomass (kg/ha)	244 (230)[a]	229 (228)[a]	80 (90)[a]
Total stand biomass (t C/ha)	0.15 (0.14)[a]	0.11 (0.11)[a]	0.04 (0.05)[a]
Total stand biomass (t CO_2/ha)	0.25 (0.24)[a]	0.19 (0.19)[a]	0.07 (0.07)[a]
Annual rate of biomass production (kg/ha/yr)	101 (95)[a]	76 (76)[a]	27 (30)[a]
Annual rate of biomass C production (t CO2/ha/yr)	0.05 (0.08)[a]	0.04 (0.06)[a]	0.01 (0.02)[a]
Annual rate of biomass CO_2 production (t CO2/ha/yr)	0.05 (0.08)[a]	0.04 (0.06)[a]	0.02 (0.02)[a]

At Lake Tutira, the annual rate of biomass production of the 2011 mānuka plantings for the 5-year period since establishment was 744 kg/ha/year. This suggests the rate of biomass production of space planted mānuka is significantly less than that of naturally reverting stands of kānuka of equivalent age at~6000 kg/ha/year (unpublished data), and is a function of the lower stand densities at this site. Similarly, at Puketoro Station the highest annual rate of biomass production of the 2013 mānuka plantings for the 3-year period since establishment was 101 kg/ha/year. Again, the rate of biomass production at this site at~27 000 kg/ha/year (unpublished data) is significantly less than that of naturally reverting stands of kānuka of equivalent age where stand densities can be up to 100 times higher than for areas established with space-planted mānuka.

Estimates of carbon are widely assumed in the local and international literature to be 50% of tree biomass (Coomes et al. 2002; Chave et al. 2004; Houghton 2005). From Tables 5 and 6 there was no significant difference in total carbon accumulation of planted mānuka across different landforms at either site. At Lake Tutira it ranged between 0.56 and 1.86 t C/ha (Table 5), and at the Puketoro Station site carbon accumulation ranged between 0.04 and 0.15 t C/ha (Table 6).

There was no significant difference in total CO_2 /ha of planted mānuka across different landforms at either site. At Lake Tutira it ranged between 0.92 and 3.07 t $C0^2$/ha (Table 5), and at the Puketoro Station site carbon accumulation ranged between 0.07 and 0.25 t $C0^2$/ha (Table 6).

12 Implications of findings

It is well known that vegetation and in particular trees, improve slope stability and reduce erosion (e.g. Greenway 1987). Several above- and below-ground growth metrics are used to compare the performance of different species for performing this erosion “protection” or reinforcement function (Stokes et al. 2009).

Tree roots reinforce soil making it stronger. The tree canopy, through hydrological processes of interception and transpiration, tends to make the soil drier, which increases soil strength. Together, both 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. Tree canopy closure is regarded as a key indicator of slope stability. 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.

However, without a long time-series of data on root growth rates and canopy diameter over a number of years, our best guesstimates of the rate of root occupancy and canopy closure at Lake Tutira and Puketoro Station are based on measurements recorded in 2015 and repeated in 2016. We compare these with measurements of root spread and canopy dimensions of individual 1–8-year-old kānuka from naturally reverting stands (unpublished data).

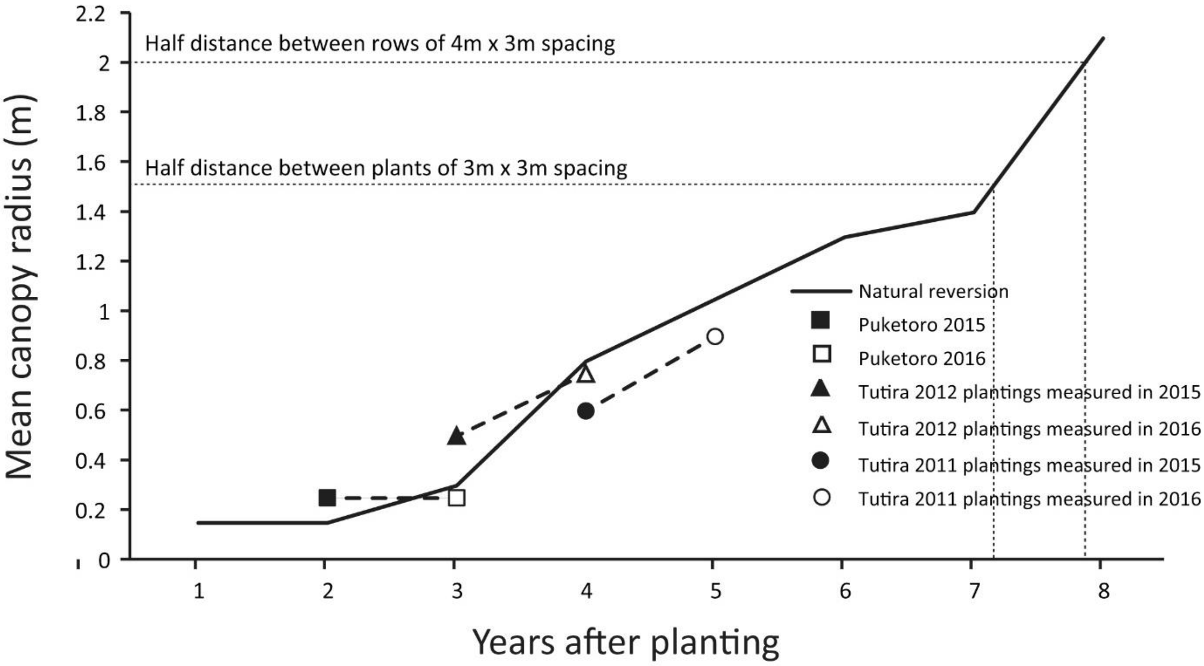

Figure 29 Mean plot-based, canopy dimensions for space-planted mānuka at Lake Tutira and Puketoro Station relative to equivalent-aged canopy dimensions of kānuka from naturally reverting stands. Dashed lines indicate approximate time required by canopies of individual mānuka to cover half the distance between plants at an even spacing of 3 m × 3 m (Puketoro Station), or half the distance between rows planted 4 m apart (Lake Tutira), to attain canopy closure. Dotted lines indicate approximate trends in canopy growth for planted mānuka and are based solely on two data points collected in 2015 and 2016.

For the mānuka plantings established in 2011 (5 years old) at Lake Tutira, the mean canopy radius in 2016 was 0.9 m, an increase of 0.3 m since 2015. Assuming the actual spacing at the time of planting was 4 m between rows and 3 m between plants within a row, and assuming a constant canopy growth rate of ~0.3 m (radius) per year based on the difference in canopy dimensions between 2015 and 2016, canopy growth appears to be marginally slower than for equivalent aged kānuka though potentially on track to achieve canopy closure 7–8 years after establishment (Fig. 29). For mānuka plantings established in 2012 (4 years old) the mean canopy radius in 2016 was 0.75 m, an increase of 0.25 m since 2015. Assuming a constant canopy growth rate of ~0.25 m (radius) in years to come, canopy growth appears to approximately that of equivalent aged kānuka and potentially on track to achieve canopy closure 7–8 years after establishment (Fig. 29). At Puketoro Station, for the mānuka plantings established in 2013, the mean canopy radius in 2016 was just ~0.25 m, and unchanged since 2015, but is nonetheless similar to equivalent aged kānuka. Canopy growth rates will likely improve as mānuka plantings emerge above the rank grass but at 3 × 3 m spacing canopy closure will be considerably delayed, given the less favourable growing conditions of altitude, wet earthflow landforms, higher proportion of unstable landforms, and higher initial mortality.

Estimates of canopy closure will also vary because of differences in canopy form/shape that are unrelated to site differences between landform units (e.g. soil thickness, composition and texture, soil moisture, nutrients, aspect and altitude) but are instead potentially related to seed source genetics, and /or the ratio of single-stemmed to multiple-stemmed plants with the multiple-stemmed plants having a bushier and denser canopy than the more slender canopy of single-stemmed plants. Windthrow, toppling, and mānuka blight may also potentially delay canopy closure. Mānuka blight is caused by the scale insect *Eriococcus orariensis* Hoy and its accompanying sooty mold *Capnodium waited* Saccardo. Mortality due to mānuka blight can be high in drier East Coast areas, with the blight appearing 3–5 years after establishment. Additionally, the timing of canopy closure will be influenced by the rate of spread of self-sown seedlings derived from nearby mature stands of kānuka. At Lake Tutira, for example, kānuka seedlings in 2015 made up half the total number of seedlings present in one plot; and by 2016 there were more than twice as many self-sown kānuka as there were planted mānuka. Additionally, self-sown kānuka were most commonly associated with colluvial slopes surrounded by stands of mature kānuka. There was no sign of self-sown regenerating mānuka or kānuka at the Puketoro Station sites.

As the canopy develops, evaporation of rainfall (interception and transpiration) and therefore its effects on the soil moisture regime of slopes (largely through hydrological processes, e.g. interception, evaporation, transpiration), will increase. In the East Coast of the North Island rainfall intercepted by the canopy of a closed stand of regenerating kānuka (*Kunzea ericoides* var. *ericoides)* accounted for 42% of the annual rainfall with interception losses higher in summer than during the winter months (Rowe et al. 1997). While interception loss as a percentage of rainfall is high compared with other interception studies of woody vegetation in New Zealand, the results are consistent with other studies if the annual losses are viewed in terms of annual rainfall, and the relationships between storm interception loss and rainfall are comparable with those for other vegetation communities including mānuka (Blake 1965; Aldridge & Jackson 1968), kāmahi (Jackson & Aldridge 1973), various forms of beech forest (Aldridge & Jackson 1973; Rowe 1975, 1979, 1983), and *Pinus radiata* (Fahey 1964; Pearce et al. 1987; Kelliher et al. 1992; Duncan 1995).

At Lake Tutira, though root growth is variable across the different landforms, and has been slower than that of kānuka of equivalent age extracted from stands of natural reversion, since

2015 there has been an exponential increase in root growth of both the 2012 (4-year old) and 2011 (5-year old) plantings. Projecting the root growth rates (limited to measurements collected in 2015 and 2016) for both age classes of mānuka planted at 4 × 4 m, it is anticipated that near full-root occupancy could occur by age 7 or 8 years (Fig. 30). On landslide scars, however, where soils are shallower and skeletal, root occupancy may not occur in areas where growth has been slower, and survival poor, or at least until the plantings are substantially older. For the 3-year-old mānuka plantings at Puketoro Station, root growth across all landforms is currently tracking behind that of kānuka of equivalent age (Fig. 30). Though a similar exponential increase in root growth is expected over the coming years, full-root occupancy of these plantings at 3 × 3 m spacing will be severely delayed, particularly on earthflows where excess soil moisture for long periods of time will inhibit root development.

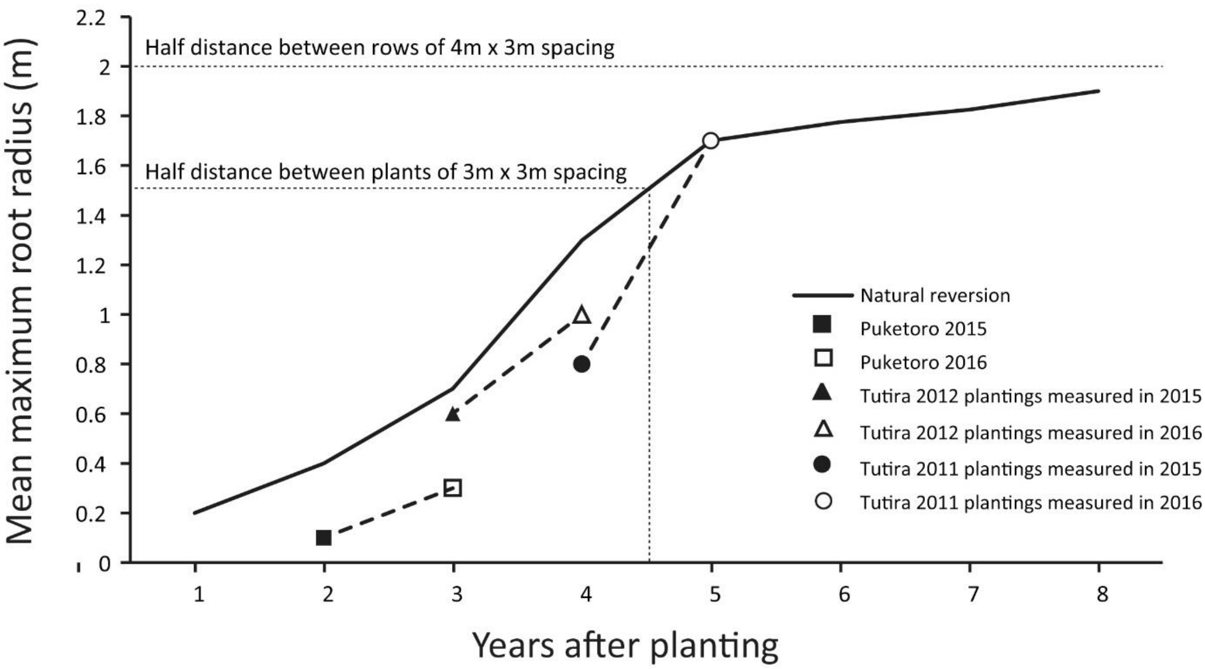

Figure 30 Mean, root growth (radius) for space-planted mānuka extracted at Lake Tutira and Puketoro Station relative to equivalent-aged root dimensions of kānuka from naturally reverting stands. Dashed lines indicate approximate time required by roots of individual mānuka to occupy the soil at half the distance between plants at an even spacing of 3 m by 3 m (Puketoro Station), or half the distance between rows planted 4 m apart(Lake Tutira). Dotted lines indicate approximate trends in root growth for planted mānuka and are based solely on two data points collected in 2015 and 2016.

In 2016, the measurement of mānuka root depths suggest that it is of the same order of magnitude as for individual plants from a naturally reverting kānuka stand of comparable age; similarly, their root:shoot ratios are comparable.

Although the above-and below-ground growth performance of space-planted mānuka at Lake Tutira is of the same order of magnitude as for a naturally reverting kānuka stand of comparable age, the level of erosion mitigation against landslide initiation at the time canopy closure is reached will not be as effective as has been previously shown for stands of natural reverting mānuka and kānuka of similar age (Hicks 1991; Marden & Rowan 1995; Bergin et al. 1995). This is because: (i) the stand canopy is less dense (although individual canopy density and leaf area is likely higher), and will not be as effective in intercepting rainfall, throughfall will therefore be greater and as a consequence soils will remain wetter for longer; and (ii) as the stem density of space-planted mānuka is at least an order of magnitude less than for an equivalent aged stand of reverting mānuka/kānuka, the area of soil occupied by roots and the density/volume of roots will be less, particularly between rows, and thus the soil–root reinforcement influences will be significantly less effective in preventing slope failure. Overall, these sites will remain vulnerable to storm events for longer.

13 Recommendations

- Canopy interception, soil–water utilisation, root biomass, and root development have been studied for naturally reverting stands of mānuka and kānuka but there is little quantitative information available for space-planted mānuka. With growing interest in the planting of mānuka on marginal land, there is a need for time-series data on changes in stand diversity, density, and in their above- and below-ground growth performance at the specified spacing prescribed for different marginal landforms.
- In particular, an extended time-series data base of below-ground growth metrics is required to better understand the effect planting density (spacing) and site factors have on the timing (years after planting) required for mānuka to provide an effective root-soil reinforcement function sufficient to ameliorate the impact of future storms.
- As the trees age, the effort and cost of data collection will increase exponentially. To spread the cost and workload it is suggested that MPI, in conjunction with Landcare Research, develop and agree to a multi-year work plan to year 2020. For the Lake Tutira plantings it is recommended that data collection continue annually until 2020. This would provide continuity in the time-series data collected to date, and importantly, span the period (years 5-7 after planting) when it is suspected that significant biomass is allocated to the development of anchoring roots. Additionally, it is suggested that sampling be restricted to only those permanent sample plots established within the 2012 age class (9 plots in total). At Puketoro Station it is suggested that data are collected from the 9 permanent sample plots every second year, that is, in 2018 (5-year-old mānuka) and 2020 (7-year-old mānuka). By 2020 trends and differences in growth performance in canopy closure and root occupancy across different terrains present at both these locations will be clear, and the time-series data collected will be invaluable for modelling the effectiveness of these plantings in mitigating shallow landslides and mass movement processes.
- With the potential for further establishment of mānuka on marginal land (predominantly for honey production), and the introduction of a new Afforestation Grant Scheme (AGS), data on the above- and below-ground biomass sequestration rates by stands of mānuka established as low-density, plantation-style plantings will be of relevance to the national carbon (C) inventory system and policy to reduce net greenhouse gas emissions. Growth metrics from these plots would provide data for the development of mānuka-specific allometric equations for calculating carbon sequestration more accurately than is possible using generalised mixed-species equations developed for older natural forest stands. It is therefore proposed that additional PSP plots be installed in other regions where significant areas of marginal land representative of different landforms have been or are likely to be planted in mānuka, e.g. Northland, Taranaki, Waiararapa, and Manawatu-Wanganui, and where climatic and site factors could significantly affect growth rates.
- As a means of promoting rates of mānuka growth and survival, evaluate the effectiveness of practices used to suppress grass competition (e.g. pre-plant spot spraying, post-plant release spraying), and trial the periodic grazing of mānuka to prevent the development of rank grass.

- Plant mānuka at densities that will achieve the desired final stocking, allowing for mortality on sites affected by past and current erosion.

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Appendix 1 – Global Positioning System locations of permanent sample plots at Lake Tutira and at Puketoro Station

Plot distribution in relation to landform units is shown on Figs. 1 & 2.

Location	Year planted	Site number	Site code	Easting	Northing
Lake Tutira	**2011**	3949	Stable interfluve 1	E2848350	N6212804
	2012	3927	Stable interfluve 1	E2846931	N6211704
		3931	Stable interfluve 2	E2847097	N6211758
		3933	Stable interfluve 3	E2847542	N6212106
		3928	Landslide scar 1	E2847022	N6211611
		3929	Landslide scar 2	E2846997	N6211662
		3932	Landslide scar 3	E2847434	N6211811
		3930	Colluvial slope 1	E2847008	N6211740
		3934	Colluvial slope 2	E2847262	N6212128
		3935	Colluvial slope 3	E2847206	N6212018
Puketoro Station	**2013**	3936	Stable interfluve 1	E2952947	N6336169
		3937	Stable interfluve 2	E2953331	N6336717
		3939	Stable interfluve 3	E2953184	N6336890
		3938	Earthflow 1	E2953246	N6336808
		3940	Earthflow 2	E2953096	N6336930
		3944	Earthflow 3	E2952684	N6336034
		3941	Slump 1	E2953117	N6336228
		3942	Slump 2	E2953162	N6336140
		3943	Slump 3	E2952961	N6336248

15.1.1 Appendix 2- General observations

Stem configuration

The majority of mānuka seedlings at the time of establishment were multi-stemmed with some plants having as many as 8 individual stems each with a separate root system. The supplier of the seedlings planted at Lake Tutira confirmed that no attempt was made to reduce the number of individual seedlings transplanted from seed trays to root trainers and that some of the plants are multi-stemmed before being planted in the field.

Grass suppression

Waist-high, rank grass and blackberry at Lake Tutira likely supressed growth and/or have deformed the stature of mānuka seedlings with many displaying a bent lower stem. This was particularly evident on the landslide scars where mānuka has been slower to establish than the grasses and blackberry. Anecdotally, the large area of pre-planting release spraying may have given the blackberry a competitive edge over the mānuka. At Puketoro Station, areas of active earthflow displacement were deliberately left unplanted, and where sedge-like grasses were well established, no attempt was made to plant through these areas. This may account, in part, for the lower than prescribed planting densities on these sites.

Soil characteristics

Soil textures on earthflows at Puketoro tend to be heavier (silty clay loam or clay loam) compared with non-earthflow terrain (silt loam or sandy loam). Topsoil depths tended to be shallower on the earthflows (mean 0.1 m) compared with non-earthflow terrain (mean 0.157 m), but only at some sites. The differences were not significant at Puketoro (Owetea site of Basher et al. 2013).

On undisturbed sites at Lake Tutira, silt loams comprise a 0.2-m thick A-horizon underlain by a 0.15-m thick B-horizon of volcanic ash (Waimihia Lapilli), and 0.4 m of older finer-grained tephra of mid-Holocene age giving a mean depth of ~0.75 m. They are free-draining with tunnel gullies forming within the Waimihia Lapilli. Soils overlie a highly weathered C-horizon of mudstone and/or sandstone and limestone. In contrast, the mean soil depth on recent landslide scars is ~0.1 m, and on older scars is ~0.3 m. The deepest soil ~1.0 m occurs on colluvial slopes where storm-initiated landslide debris has accumulated over many years (Preston 1999).