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Pastoral Hill Slope Erosion in New Zealand and the Role of Poplar and Willow Trees in Its Reduction

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1. Introduction

1.1 The geology of New Zealand and its contribution to erosion

New Zealand is a predominantly hilly and mountainous country. An area of 18 million hectares (69% of the country) has slopes greater than 12°, and is commonly called 'hill country'. This is further divided into 'hill-land' (12–28°) and 'steepland' (if slope exceeds 28°) (DSIR 1980). The range of slope and elevation, coupled with a wide latitudinal range, a mid-oceanic setting encompassing subtropical to cool temperate climates, and complex geologic and tectonic regimes means that New Zealand's 'hill country' is physically diverse. As a consequence of this diversity, the productive potential of New Zealand's' hill country, and its response to climatic events, land use pressure and environmental change varies significantly across the country.

Erosion is a significant environmental issue facing agricultural and forestry land uses in large parts of the hill country of New Zealand. It causes both on-site (loss of soil productive capacity and water holding capacity) and off-site (declining water quality, river aggradation, increased vulnerability of infrastructure to severe climatic events) effects. As well as the environmental costs there are major financial risks and social consequences, at every organisational level, of repeated erosion and flooding events.

Of the 6.3 million hectares in the North Island, the majority is developed on soft rock and crushed soft rock terrain in the south-east and west of the island (2 825 000 ha, 45%). Volcanic ash and loess-mantled terrain comprises another 23% (1 456 000 ha), largely on the periphery of the Central Volcanic Zone. Hard rock hill country, exclusive of the igneous hard rock hill country, is largely concentrated on the margins of the axial ranges (919 000 ha, 14.5%), whereas the hill country developed on deeply weathered sedimentary and igneous rocks (863 000 ha, 13.6%) is located predominantly in Northland and on the Coromandel Peninsula. In the North Island approximately 200 000 ha has a mapped erosion severity of severe, very severe or extreme. The North Island hill country is dominated by mass movement erosion. Shallow landslide (soil slip) and sheet erosion are the most widely distributed followed by earthflow and gully erosion. Sediment yield is highest in the northern East Coast Region, and high throughout much of the rest of the East Coast, inland Taranaki and parts of Northland. Mean sediment yields are highest in the crushed soft rock hill country and hilly steeplands, and steep soft rock hill country (Basher et al., 2008).

In contrast to the North Island, 56% of the South Island's 3.7 million hectares of hill country is developed on hard rock terrain. Only 569 000 ha is developed on soft rocks. Steep weathered hill country is associated with both schist and greywacke. In the South Island less than 103 000 ha has an erosion severity ranking of severe, very severe or extreme. Unlike the North Island, the South Island is dominated by surface erosion types. Sheet and soil slip erosion are the most common forms of erosion in the South Island hillcountry. Tunnel gullying is far more common in the South Island while gully and earthflow erosion are far less common. Sediment yields tend to be far lower in the South Island and are highest on the West Coast because of the higher rainfall. Mean sediment yields are highest in the steep soft rock hill country (Basher et al. 2008).

1.2 Erosion processes on Hill country

New Zealand is widely recognised as having high rates of both natural and man-induced erosion. The extent and type of natural erosion is determined by the complex interplay between geology (rock type, weathering, structure, and regional plate tectonics), climate (particularly rainfall amounts and intensities, frequency of large storms) and vegetation, producing regional variation in the susceptibility of the land to erosion. Severe earthflow and gully erosion are closely related to the extensive areas of mudstone and crushed rock terrain in the North Island, whereas in the South Island gully erosion is largely associated with hill country developed on easily eroded soft mudstone, sandstone, weakly consolidated conglomerate, and regional fault and crush zones. Annual rainfall is the dominant factor influencing rates of erosion, as measured by suspended sediment yields, and numerous studies point to the importance of large storms as triggers for widespread landsliding (Griffiths 1981, 1982; Hicks et al. 1996).

Imposed on these natural drivers of erosion is the effect of historical deforestation and land use which has increased erosion to a greater or lesser degree depending on the lands' inherent susceptibility to erosion. Numerous studies demonstrate the linkage between increased sedimentation rates, European settlement and deforestation (e.g. Page et al. 1994a, b). Deforestation can lead to at least a 10-fold increase in erosion both in the long term and during large storms, while short-term sediment yield increases of up to 100 times after forest harvesting have been recorded (e.g. Fahey et al. 1993). Much of the increase occurs when the tree roots lose their strength, about 2–5 years after forest removal. However, the impact of deforestation persists in many deforested areas with thick regolith or soft rocks which continue to erode faster than similar forested areas for at least a century (Page et al. 2000).

Landslides are the best studied erosion process, are very widespread, and a major contributor to hillslope erosion and sediment yield. Crozier (2005) concludes that most common landslide events are triggered by storm rainfall with critical intensities governed by the prevailing antecedent moisture conditions, rainfall duration and amount. Since the onset of European deforestation, increased sediment production over much of New Zealand has largely been determined by landslides (Glade 2003). On unstable slopes, thousands of landslides can be triggered by high-magnitude/low-frequency climatic events during storms with estimated return periods in excess of 50 years (e.g. Glade 1997, 1998, 2003).

In contrast, gully (e.g. De Rose et al. 1998, Betts et al. 2003; Marden et al. 2005; Parkner et al. 2006, 2007, Fuller & Marden 2011, Marden & Herzig, 2011) and earthflow erosion (e.g. McConchie 1986; Zhang et al. 1991, 1993; Trotter 1993, Marden et al. 2008) are far less well studied. However, in at least some East Coast areas gullies cover much less area than landslides but make a far larger contribution to sediment yield as low-magnitude/high frequency rainfall events activate gully erosion (Page et al. 2000, Marden et al. 2008).

2. Hill country erosion control practices

New Zealand is unique in the way it uses its steep and often unstable hill country for pastoral farming, grazing predominantly sheep and beef cattle but also deer. Stock remain on the hills all year round, except in the high country during winter.

2.1 History of using poplar and willow for erosion management in pastoral hill country

Following deforestation (1.1), pastoral hill country erosion became so severe, the Water and Soil Conservation Act was passed by the New Zealand Government in 1941. This Act set in place an administrative structure of Catchment Boards tasked with controlling soil erosion and flooding, directed by central government policies. Central government funded applied research and grants to Catchment Boards till 1988. In 1988 the Catchment Boards became Regional or Unitary Councils responsible for managing a wide range of environmental activities including soil erosion and flood control. A new act, the Resource Management Act (RMA) of 1991, is now the guiding legislation for erosion control.

Erosion control measures for pastoral hill country were required to be established in the presence of the grazing animal, with permanent retirement from grazing recommended only in the most extreme situations. Only tree-based control measures were affordable on the scale required. The main beneficial effects of trees on the mass stability of the slopes are well described by Gray and Sotir (1996, pp 59-61). The two most suitable tree species proved to be poplar (*Populus* spp) and willow (*Salix* spp). Both species are readily established from large poles in the presence of stock, with a minimum of protection, are able to be produced cheaply in nurseries, and are easily transported and planted on steep unstable hill country. They grow quickly, can tolerate wet soil conditions for long periods, and do not shade pasture growth to any degree unless planted at close spacing. They are protected from stock browse by plastic sleeves placed over the poles at planting time which are removed after 4 or 5 years when the bark is able to resist stock rubbing and stripping. Their added values to the pastoral site through shade, shelter, quality fodder (especially during drought periods) and carbon sequestration, increase their utilisation by landowners.

2.2 Using poplar and willow for erosion control on pastoral hill country

This section describes recommended practices employed by landowners or land managers to prevent or reduce the more prevalent forms of erosion on pastoral hill land. Usually the erosion control is operating where earlier erosion events have occurred. Almost all pastoral hill slopes in New Zealand show signs of past erosion events. Landslide erosion control is given most attention for the reasons given in 1.1. Landslides affect much greater areas of land, are more widespread geographically, and have significant economic impact (see 3.1). The focus of the root research activity described later in this chapter is on slope protection against landslides. Control of other erosion types will be covered briefly.

2.2.1 Landslide erosion control

Landslides of the nature seen in figure 1 (L) follow a major rainstorm event and can happen at any stage of the year. Herbaceous plant cover alone on these pastoral hill slopes offers insufficient resistance to landsliding. To prevent the occurrence of landslide, or to prevent further landsliding, willow or poplar poles are planted up to 15 m spacings across the slope in a regular pattern or, more usually, where further landsliding is considered most likely to occur (Figure 1 R). Landslide prone soils are often shallow and exposed to climatic extremes.

Fig. 1. Severe slipping on soft sandstone (L); young space planted poplars reduce the risk of further erosion on an unstable slope (R).

The recommended approach is to plant a mix of clones and actively manage them (e.g. protection, replace dead trees, no cattle exposure for 2-3 years) for the first five years of growth to ensure a healthy tree develops. Willows are usually preferred in the wetter areas and lower on the slope where they are better adapted and the soil moisture is higher, while poplars are favoured further up the slope. Spacings are reduced where there is water ponding (Hathaway 1986). Pole planting is done in winter, either by ramming the sharpened pole directly into the moist soil or planting into an augured hole. Newly planted poles are revisited in summer to ram contracted soil around the pole. Survival rates of 90% are often achieved for poplars and willows planted from poles. Any dead poles are replaced the following winter. Tree death from animal damage is reduced by covering the poles with a plastic sleeve and excluding cattle from planted areas up to three years. Where the potential for slip erosion is very severe to extreme a closed canopy tree cover is recommended. However, this requires permanent retirement from pasture, a change many farmers are not willing to undertake.

2.2.2 Earthflow erosion control

Willows are preferable to poplars for slowing earthflows as their roots form thick mats when in a wet environment. Earthflow control measures rely on removing surface water to minimise infiltration by surface smoothing and constructing diversion banks, tying together the surface with willow roots, pair planting willows where gullies are likely to form and planting at the toe of the movement to hold up the toe (essential when the toe is being undercut by a waterway). Spacing is closer for wetter or more active earthflows.

2.2.3 Slump erosion control

These events are usually sufficiently large that tree planting alone will not control them. They require surface water to be drained, the surface smoothed, retired from grazing and close planted in trees. Once in trees they need to be managed as continuing movement will overturn or topple trees requiring clearing to keep drainage open, and replanting. Over time movement will reduce.

2.2.4 Gully and tunnel gully erosion

Discontinuous gullies are very common in pastoral hill country. Large erosion events fill the valley bottoms and smaller events begin to scour them. Control of further erosion is achieved by pair or single planting willows up the valley bottom at 15-20 m spacings and, at points with serious erosion, developing a planted block with 2-3 rows of willows planted at 1.5m spacings across the valley bottom and in an area fenced out from grazing. Erosion from small gullies has been successfully arrested by construction of debris dams at intervals up the gully coupled with pair planting of willows. The willow root mats growing across the gully bed and over the surface of the dam cover and isolate the eroding surface. Drainage lines supplying the gully are pair planted with tree willows at 15-20 m spacings and measures taken to ensure the grassed surface is not broken, allowing a gully head to form. Terrace edges are protected by either grassed waterways or constructed flumes. To stabilise very large gullies often requires the whole catchment to be retired from grazing and planted in closed canopy trees. Where climate allows trees to grow, tunnel gully erosion is controlled by planting a poplar or willow pole in the collapsed tunnels. Further tunnel erosion is prevented by planting poles in the characteristic sunken drainage lines supplying the tunnel. The tree roots hold up the sediment gradually filling up the holes.

2.2.5 Stream bank erosion

In hill country, storm events create flash floods resulting in bank scour and deepening the channel to form a gully. Stream bank protection is achieved by planting willows or poplars along the banks. The roots stabilise the banks and protect the stream bed from degrading. Large limbs are removed from mature stream bank trees to rejuvenate them, reduce their size and reduce risk of bank destabilisation.

3. Effectiveness of trees in reducing erosion on pastoral slopes

Knowledge of the effectiveness of trees in stabilising soil and reducing erosion potential on slopes is important when considering time scales, costs, landowner attitudes to topsoil displacement and loss and the achievement of catchment scale objectives for managing consequences of silt incursion into waterways.

3.1 Effect of hill slope erosion on pasture production

Landslide erosion results in immediate and often dramatic reductions in pasture production on steep hill country (Lambert et al. 1984). Reductions in land productivity from soil erosion occur directly through the loss of topsoil, and indirectly through reduced pasture yields on eroded ground (Blaschke et al. 1992). Quantification of economic and biophysical losses associated with landslide erosion is crucial to justify the need for soil conservation and erosion control activities on steep hill country. An understanding of the rate of recovery of

production on landslide scars is essential for implementing improved farm management techniques and land uses. Measured pasture dry matter yields on young landslide scars were ~20% of the yields produced on un-eroded ground, and while such scars revegetated rapidly over the first 20 years and could attain 70–80% of original productivity, further recovery was slow (Lambert et al. 1984, Rosser & Ross 2010). Maximum pasture recovery occurred within about 20 years of landsliding and further recovery beyond 80% of un-eroded level is unlikely (Lambert et al. 1984, Rosser & Ross 2010).
Loss of pasture production reflects loss of soil physical and chemical properties. Recovery of pasture production on landslide scars follows similar recovery to soil physical (soil depth, particle density, etc.) and chemical properties (Total C, total N, etc.). Topsoil depths on eroded sites were roughly a third of topsoil depths on uneroded sites, indicating reduced profile available water capacity on eroded soils (Rosser and Ross 2010). However, data were inconclusive on whether surface total C would recover to values on uneroded sites in the long term. Other soil properties (C/N, pH, Mg, Na, and CEC) are expected to recover to uneroded values within human time scales and are not the cause of permanent reductions in pasture growth on older landslide scars. The implications of this and previous research are that the sustainability of pastoral agriculture on steeper east coast hill country, underlain by poorly consolidated parent materials, will come increasingly under threat from the progressive reduction of pasture production through cumulative erosion.
The economic costs of pastoral hill country erosion are under-researched and under-reported in New Zealand.

3.2 How effective are *Populus* and *Salix* in reducing erosion?

Erosion control plantings of trees hold many advantages over herbaceous ground cover in their capacity to bind soil at deeper levels, improve slope drainage, anchor the soil to bedrock through root penetration and establishment, reduce the impact of rain on the soil surface, provide a barrier to downward movement of soil, redirect rainfall via flow to parts of the slope with high protection (i.e. near the stem), re-evaporate rainfall from leaves and branches. However, the presence of soil conservation poplar or willow trees on pastoral slopes does not ensure that erosion by slippage or earth flow will not occur. The trees might be described as effective in preventing erosion only when there is no slippage or if slippage is restricted to very short movements follow prolonged rainfall and soil saturation. Factors determining effectiveness include planting density, tree spacing, tree root length density, tree root mass density, location of trees in relation to slope topography and water movement, age of trees.
Few published data are available on the effectiveness of space-planted *Populus* and *Salix* trees in reducing hillslope erosion. Hawley and Dymond (1988) using digital image analysis of aerial photographs, and a derived relationship between the fraction of ground eroded (landslide scars) and distance from a tree, estimated the degree to which individual trees of *P.* × *euramericana* aged 14-17 years reduced shallow landsliding following a recent severe storm. The tree spacing was 25 sph, though with some mortality. They concluded that an average *Populus* tree saved 8.4 m^2 of ground from failure. thereby reducing pasture production losses by 13.8% compared with equivalent untreed sites. At spacings of 10 m x 10 m (100 sph) and assuming 100% tree survival, they estimated that immediate pasture production losses attributable to landslides would have been reduced by at least 70%, compared with 13.8% at a tree spacing of 25 sph. Hawley (1988) also predicted that for two

trees spaced 11.5 m apart (75 sph), land slippage around one tree, including the contribution from a neighbouring tree, would be reduced from 8.2% to about 1.45%, that is, by about 82% of that previously. A more comprehensive study by Douglas et al. (2011) covering 53 sites with *Populus* trees, 6 sites with *Salix* trees and 6 sites with *Eucalyptus* trees recently exposed to a severe storm event showed that over all sites, trees reduced the extent of slippage by an average of 95% compared with slippage on nearby pasture control sites. The treed sites contained groups of trees varying in number from 4-10, and at densities ranging between 32 sph and 65 sph. Slippage occurred at 10 of the 65 sites, and the greatest extent of slippage occurred where trees had a diameter at breast height (DBH) of <30 cm. They concluded that spaced *Populus* and *Salix* trees dramatically reduced the incidence and severity of soil slippage on erodible slopes, and that they were even more effective when their average DBH was 30 cm or greater. Mature plantings of 30-60 sph (13 m to 18 m spacing) were very effective in controlling soil slip erosion.

There is a paucity of data on the effectiveness of spaced *Populus* and *Salix* trees with DBH <30 cm in reducing slope erosion in New Zealand hill country. Firm recommendations can be made on planting density for mature trees, but it is clear that higher planting densities are needed for younger trees if they are to reduce slippage to the same extent and in fact they are not likely to be effective at all until some years after planting, depending on growth rate and exposure to severe storm events.

4. Root behaviour of poplar and willow trees on slopes

One of the key ways trees and other woody vegetation contribute to slope stability and control a range of erosion processes is through their development of root networks that enhance the mechanical reinforcement of soil (Phillips and Watson 1994; Genet et al., 2008; Stokes et al., 2009; Schwarz et al., 2010). Roots provide reinforcement to soil through a combination of their tensile strength, frictional resistance, and soil bonding properties (Schmidt et al., 2001; Bischetti et al., 2005, 2009; Genet et al., 2005; De Baets et al., 2008). The major factors that determine the degree to which tree roots modify soil reinforcement are root system architecture and tree density, which are influenced by factors including species, tree size, topography, soil characteristics (e.g. depth, texture, bulk density, water content), and above-ground management (Roering et al., 2003; Reubens et al., 2007; Stokes et al., 2009).

Although poplars and willows have been used in New Zealand for a range of erosion control programmes for more than 50 years (Thompson and Luckman, 1993; Wilkinson 1999; Douglas et al., 2011), before 2000, few studies were conducted or reports written to gain knowledge and understanding of their root systems and their strength and how they vary spatially and temporally (Hathaway 1973, 1986; Hathaway and Penny 1975; Vine 1980; Luckman et al., 1981; Hughes 1992; Wilkinson 1999). Laboratory testing found that the tensile strength of poplar and willow roots collected from 1-year-old trees ranged from 36.3 to 45.6 MPa and samples from different seasons varied in strength possibly because of variations in specific gravity and the ratio of lignin to cellulose (Hathaway and Penny 1975). At Palmerston North in the southern North Island, Vine (1980) excavated the roots of six species or clones of poplar aged 3-6 years and examined roots greater than 5 mm diameter. The root systems were asymmetric, exhibiting strong growth into unplanted areas, and root grafting was observed between adjacent trees. There was considerable variation in vertical and lateral root growth between species or clones, and between trees within clones. Hathaway (1986) reported that few data were available on root system morphology and root density of soil conservation plants under New Zealand conditions. Consequently, recommendations on appropriate species and clones for erosion control on specific sites were based almost entirely on survival and above-ground characteristics, and practitioner experiences. Near Palmerston North, roots of poplar trees aged 5 or 6 years growing at a site with a free-draining soil and another site with restricted drainage were sampled by intensive coring to a depth of 1 m (Hughes 1992). Very few large woody roots (> 2.5 mm diameter) were found at the poorly-drained site compared to the well-drained site, because a number of large roots were likely killed during periodic wet periods at the moister site. The few roots present at depth and at the periphery of the poorly-drained tree rooting volumes were non-woody fine roots. Across diameter classes, woody roots were detected up to 1 m depth in the free-draining soil whereas in the soil with poor drainage, they occurred at less than 0.7 m depth except for a root < 2.5 mm diameter found at 0.75 m depth and about 0.3 m from the tree. Woody roots were found up to 4.3 m from trees in the poorly-drained site and up to 5.3 m from trees in the well-drained site. Wilkinson (1999) listed nine principal reasons for using poplars and willows for erosion control, one of which was their extensive root systems capable of rapidly stabilising large soil masses. He reported that annual extension of their roots across and downslope was similar to their annual height increment (m) while upslope extension occurred at about half of that rate. No further details were presented and it is uncertain if these findings were from research conducted in New Zealand or overseas.

4.1 Recent studies

With changing research emphases and enhanced funding in sustainable land management and related areas over the last decade, the distribution and other characteristics of roots of poplar and willow, and factors that influence them, have been determined (McIvor et al., 2005, 2008, 2009; Douglas et al., 2010a, b; Marden and Phillips 2011). On a research farm near Palmerston North, the distribution of coarse/structural roots (> 2 mm diameter) of young trees of *Populus deltoides* x *nigra* 'Veronese' (diameter at breast height (DBH) < 30 cm) of different age and size (McIvor et al., 2008), and position on a slope prone to shallow landslides (McIvor et al., 2009), was determined by whole-tree excavation. The trees were established by planting 3 m poles (vegetative cuttings), the usual establishment method for this species (Wilkinson 1999), on an east-facing slope of 15-25^{o}. The distribution of radial roots of individual trees aged 5, 7 and 9.5 years growing lower on the slope (< 20^{o}) on an accumulation zone (relatively deep soil) was variable around the trees at each age and differed between upslope and downslope sides of the trees (Figure 2, McIvor et al., 2009). Roots of trees at each age were distributed asymmetrically with those of trees aged 5 and 9.5 years aligned in a similar direction of left/upslope to right/downslope. In contrast, the roots of the tree aged 7 years were concentrated in the left/downslope quadrant. Across all trees, radial roots were generally found within 0—40 cm soil depth and often within 0-15 cm depth. Vertical roots extended to a depth of about 1.0 m, where a fragipan occurred. Total root dry weights (excluding root crown) were 0.57 kg (tree aged 5 years), 7.8 kg (7 years) and 17.9 kg (9.5 years), and total root length was 79.4 m for the tree aged 5 years and 663.5 m for the 9.5 year-old tree (Table 1). A linear relationship was established between root mass and DBH (Root mass = 1.16*DBH - 7.56) and between root length and DBH (Root length =

45.1 *DBH - 293.4). The results indicated that root development of the trees was minimal in the first 5 years but then increased rapidly. It was suggested that poplar trees established from poles on erosion-prone slopes needed to attain at least 5 years to develop a structural root network that binds soil effectively.

Tree Age yr	Height m	DBH cm	Position on slope	Slope angle	Above ground mass kg	Below ground mass kg		Coarse Root length m
						root	crown	
5	7.3	8.4	Lower	22.0	10.49	0.57	x	79.4
7	9.3	14.4	Lower	21.3	43.52	7.8	x	349.3
9.5	13.3	21.3	Lower	22.1	132	17.9	3.3	663.5
11	13.4	29	Lower	21.8	260.79	81.35	18.18	1611.3
11	12.95	27.2	Mid	28.6	210.87	38.77	16.5	1131.3
11	11.15	18.9	Upper	32.0	61.48	8.15	6.6	293.2

Table 1. Dimensions of six *Populus* × *euramericana* 'Veronese' trees excavated on a pastoral hillslope.

In a sequel investigation in the same planted block, McIvor et al. (2009) determined the effect of slope position (upper (slope angle 32^o), mid (28.6^o) and lower (21.8^o)) on root distribution and other root characteristics of 'Veronese' poplar aged 11.5 years (Table 1). At each position, trees (sample size = 1) had DBH of 18.9 cm (upper slope), 27.2 cm (mid) and 29.0 cm (lower). Most of the > 2 mm diameter roots occurred within 0-40 cm soil depth.

Radial distribution of roots varied between slope position with distribution at mid- and lower slopes being more symmetrical than at upper slope where roots were mainly directly upslope of the tree and west of the tree (Figure 2). Roots spread at least 8 m in one direction around each tree, and in some cases more than 10 m. They changed direction and depth frequently and crossed each other regularly. Roots growing downslope were mostly located within 30 cm of the ground surface and changed depth less often than roots in the upslope direction. Growth of vertical roots varied with position and depended primarily on soil depth to a fragipan, ranging from 0.35 m at the upper slope to 1.4 m at the lower slope. Roots penetrated the fragipan at the upper and mid-slope positions but not at the lower slope position where soil depth was greatest. Total root length ranged from 287.9 m (upper slope) to 1,611.3 m (lower) and total root dry weight (excluding root crown) ranged from 8.15 kg (upper) to 81.35 kg (lower). Earlier relationships between root mass and DBH, and root length and DBH (McIvor et al., 2008), were revised with inclusion of data collected in this study to give exponential relationships of Root mass = $0.0003*DBH^{3.62}$ and Root length = $0.6582*DBH^{2.26}$. Both studies by McIvor et al. (2008, 2009) involved trees that were likely far enough from adjacent trees to minimise any above- or below-ground interactions with them. The findings were valuable because they provided knowledge and understanding of essentially isolated trees on slopes, and hence full expression of the measured root traits under the prevailing topographic and climatic conditions.

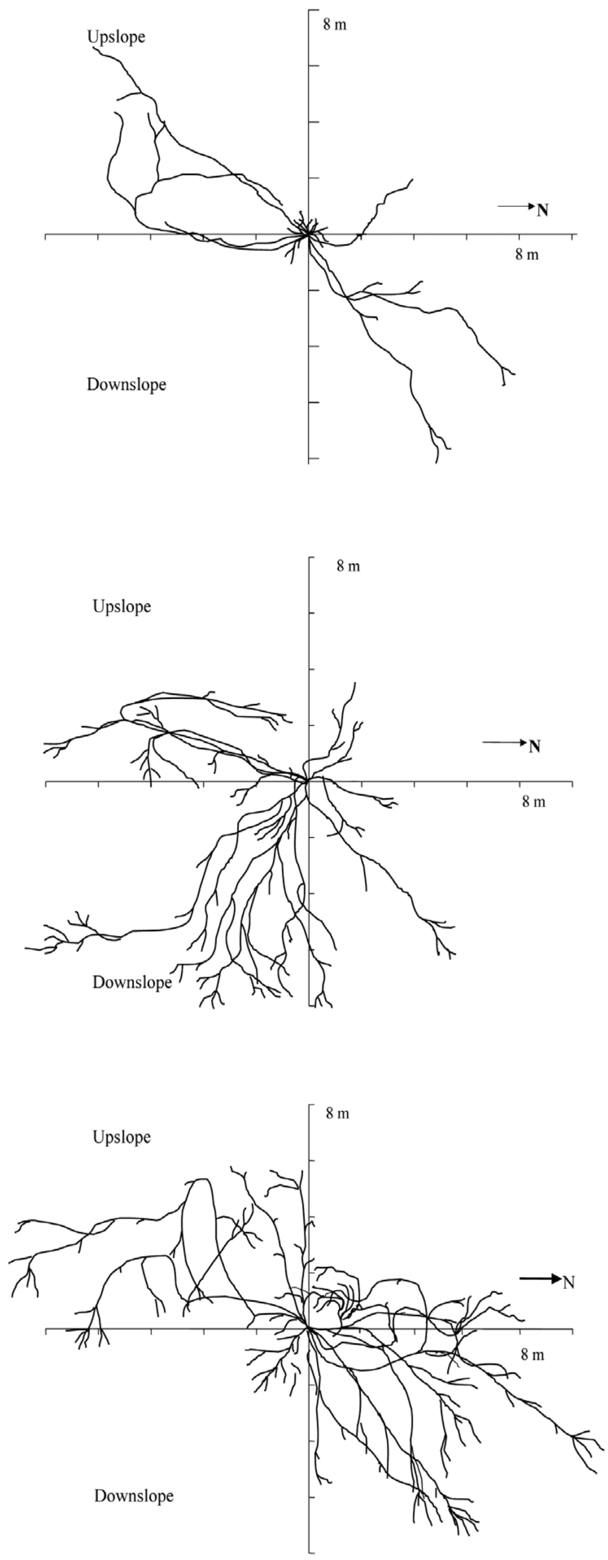

Fig. 2. Radial distribution of structural roots (>2 mm diameter) of 'Veronese' poplar trees aged 5 yr (top L), 7 yr (top R) and 9.5 yr (bottom) growing on hill country near Palmerston North (from McIvor et al. 2008).

4.2 Density effects

The next phase of research determined the effect of tree density or spacing on root distribution of poplar. Planting densities of 25-256 stems ha^{-1} have been recommended but little is known of how the root system develops chronologically and what root densities different planting densities achieve. Two studies were conducted near Palmerston North involving 9-11 year old poplar, mostly *Populus deltoides* x *nigra* 'Tasman', arranged in a Nelder planting design, and involved excavating trenches between adjacent trees to a soil depth of 90 cm. In the first study, trenches were dug in four directions around single trees at densities of 84 and 770 stems per hectare (sph) growing on slope angles of 3.5-5.5^o (McIvor et al., 2005). Most of the roots were within 0-45 cm soil depth and the number of roots decreased exponentially with depth. For example, at a distance of 0.9 m from the tree at 770 sph, root number decreased from 398 roots/m^2 at 0-15 cm depth to 6 roots/m^2 at 75-90 cm depth. At 770 sph, the tree root network at any point was contributed by more than one tree. At the low density planting, there were no roots found at the midpoint between adjacent trees. Around both trees, there were no significant differences between root number and root cross sectional area at each of the four directions, suggesting that the root systems were distributed symmetrically on these low slope angles. It was suggested that for tree plantings at this age, the ideal planting density for both pasture production and erosion control is likely to be between 84 and 770 sph.

Additional tree densities were included in the study by Douglas et al. (2010a), and involved 84, 89, 160, 210, 237 and 770 sph. More than 80% of roots were < 5 mm diameter and root number and root area ratio (RAR) were higher in shallow soil layers e.g. 0-15 cm depth than deeper in the profile. Trees at 770 sph had 3-12 times more roots and 3-9 times greater RAR than those at other densities. Mean cross-sectional area per root was 3.5-4.8 mm^2 and did not vary significantly between densities. Densities of 160, 210 and 237 sph had moderate to high root occupancy of soil layers and satisfactory root number and cross-sectional area. They were therefore recommended as options to enhance soil strength whilst likely enabling satisfactory understorey pasture production. Using the 160 sph density rather than the two higher densities would reduce planting material and labour requirements and potentially increase pasture growth.

4.3 Root length density effects and seasonal changes

Current research is investigating the root occupancy of the root network to complement the radial distribution of whole tree excavations and the vertical distribution from trench studies. Root length density (RLD) is a way of describing root occupancy. Coring provides data on both coarse and fine roots for a particular volume of soil from which RLD can readily be calculated, and has led to understanding of the contribution of fine roots to the root network and calculation of RLD was determined from cores for wide spaced trees of *Salix matsudana* × *alba* 'Tangoio' and *Populus* × *euramericana* 'Veronese' growing on pastoral slopes of varying steepness from 14° to 21°, and from 21° to 32° respectively. Cores of diameter 200 mm were taken in 150 mm intervals to 600 mm depth at fixed distances of 2 m and 3 m (willow) and 2 m and 4 m (poplar) from the stem and at positions 120° apart to allow for asymmetrical root distribution. For the willows, in the summer of 2009 and 2010 respectively, 71.3% and 83.5% of root length density (RLD) was found in the upper 300 mm with as much as 67.4% of RLD being in the top 150 mm of soil (Table 2). While the % of RLD from 300-600 mm depth decreased from 2009 to 2010 in absolute terms the RLD had changed little (Table 2). The % contribution of fine roots to total RLD varied little between depths and sample times, and ranged from 89 to 93. RLD is contributed largely by fine roots whereas root mass density is contributed by coarse roots (Figure 3). Fine RLD was much higher in the upper 150 mm of soil in 2010, though not at lower depths. Fine root production is particularly responsive to soil moisture. For the poplars % RLD in the upper 150 mm ranged from 65% down to 17%, and in the top 300 mm ranged from 78% down to 43%. RLD was similar at the different distances from the stem for both species. Vertical distribution pattern of RLD in willow from core data and RAR in poplar from the trench data are very similar, whereas there are notable differences in root distribution between trench and core data for poplar. On steeper slopes RLD is possibly more evenly distributed through the soil profile. Further studies are needed to verify this hypothesis. To fully understand root occupancy distribution RLD should be measured to 10 m from the stem. There was a significant reduction in RLD during the dormant season in both *P.* × *euramericana* 'Veronese' and in *S. matsudana* × *alba* 'Tangoio'. The reduction in RLD was almost entirely through loss of fine root, with little change in coarse root RLD and was more pronounced in the top 300 mm for both species. For example, the ratio of fine RLD to coarse RLD for *P.* × *euramericana* 'Veronese' poplar reduced from ~15x at the end of summer to close to 1x during the dormant period of the year (Figure 4). The replacement of fine roots lost during the dormant period happens quickly once the trees become active, which happens earlier for willows than for poplars. The reduction of fine RLD during the dormant season provides more pores for water storage and drainage, but reduces the root-soil contact significantly, and the cohesive soil-root network strength will reduce accordingly. Further research is needed to know what constitutes sufficient soil-root network strength for slope stability in the pastoral hill country situations where these trees are being planted.

Year	Soil depth	Root Length density mm^{-3}			% allocation of RLD
	mm	Fine Roots	Coarse roots	All roots	
2009	0-150	1769	210	1979	41.5
	150-300	1374	43	1418	29.8
	300-450	601	47	648	13.6
	450-600	654	71	725	15.1
2010	0-150	4303	321	4624	67.4
	150-300	1013	90	1103	16.1
	300-450	558	57	615	8.9
	450-600	478	41	519	7.6

Table 2. Mean root length density (mm^{-3}) of mature *Salix matsudana* × *alba* 'Tangoio' measured at 2 m from the stem in two consecutive years (DOY 49 2009, DOY 47 2010)

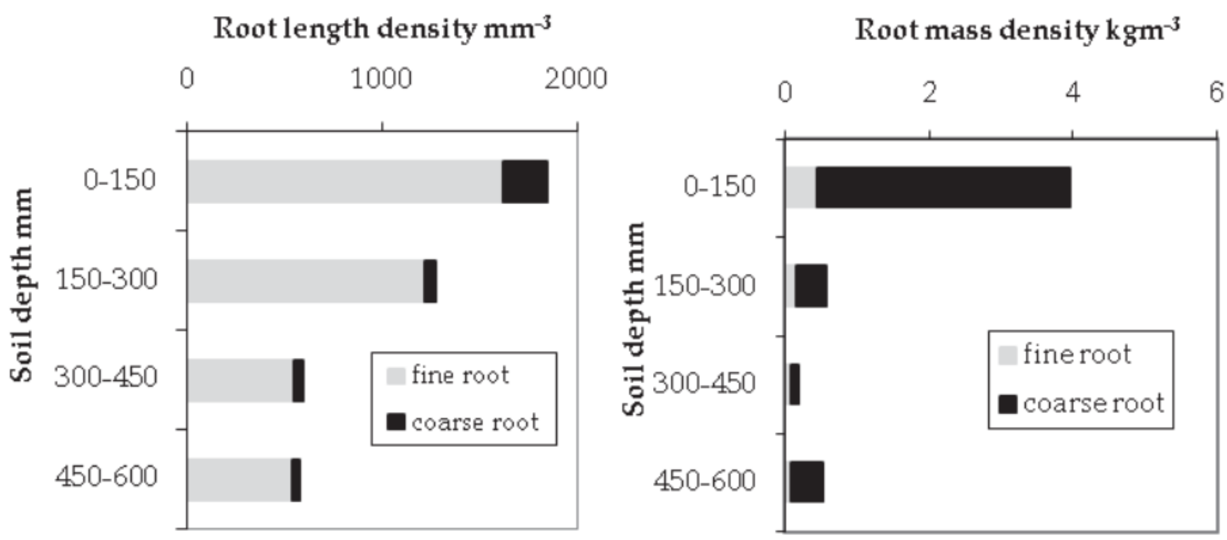

Fig. 3. Fine (< 2 mm diameter) and coarse (≥ 2 mm diameter) root length density (L), and fine and coarse root mass density (R) of *Salix matsudana* × *alba* 'Tangoio' varying with soil depth.

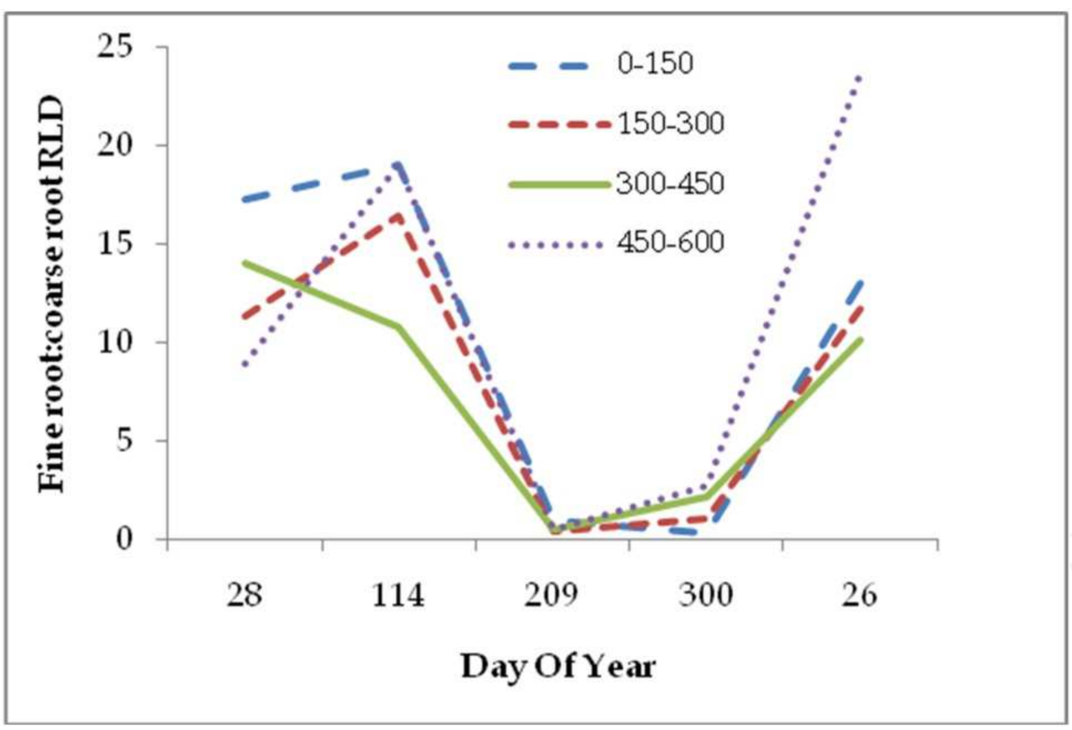

Fig. 4. Fine root RLD: coarse root RLD for *P.* × *euramericana* 'Veronese' poplar at different soil depths (mm) over one year.

4.4 Methodology

Studies of poplar and willow roots in New Zealand have only used whole-tree excavation (e.g. McIvor et al. 2009), trenching (e.g. Douglas et al., 2010a), and coring (McIvor et al. 2010) methods. Whole-tree excavation has many advantages including enabling complete understanding of root distribution, insights into growth and external morphological changes in roots outwards from a tree, classification into diameter classes, determination of total root mass and total root length, and providing data for use in models e.g. 3-D architecture models. However the method is very time consuming e.g. 10-15 person days for excavating a young tree, difficult on steep slopes, and tree removal weakens a site prone to various erosion processes. Trenching and coring provide samples from the whole root system, and therefore are prone to sampling variation, including for coring, obtaining samples without roots. Both methods exclude vertical roots extending from the central tree axis, which are important for potential penetration into underlying bedrock/fractures and anchorage. There has been limited investigation of the potential of chemical analysis methods e.g. dyes, and ground penetrating radar for studies on poplar and willow roots.

4.5 Root tensile strength of *P.* × *euramericana* 'Veronese' poplar

Roots sampled from 'Veronese' poplar trees aged < 10 years and growing on a slope angle of 23-27° (McIvor et al. 2008) were tested for tensile strength (Watson et al., 2007). Undamaged roots with over-bark diameters of 1.16-12.63 mm (under-bark diameter 0.90-8.51 mm) and 150-250 mm long, collected within 0-250 mm soil depth, were tested. A power function relationship was developed between live root-wood tensile strength (Y; MPa) and under-bark diameter (X; mm) using 123 samples, of $Y = 80.79*X^{-0.82}$ with an r^2 value of 0.69.

Mean tensile strength decreased rapidly over the range 1-3 mm diameter, being 90.8 MPa for roots < 1mm, 56.9 KPa for roots 1-2 mm, and 40.1 MPa for roots 2-3 mm diameter (Figure 5). Root diameters of 3-9 mm had mean tensile strengths of 19.0-24.3 MPa. The decrease in tensile strength with increase in diameter may be a function of the changing material properties of the root-wood (e.g. cellulose) with increase in root size (age), an increase in the number or severity of defects with increasing root size, or other factors.

4.6 Current research

There is increasing awareness of the need to manage poplar and willow trees planted for soil conservation. As trees age, they can become large and prone to limb breakage and toppling e.g. under high winds, potentially damaging farm infrastructure (tracks, fences, buildings etc.), injuring livestock, and creating debris that can hinder livestock mustering and other operations. The practice of pollarding, involving the removal of the entire canopy, has been advocated for numerous poplar and willow plantings, to prevent large trees developing, and supplying supplementary fodder for livestock during feed shortages such as summer/autumn drought. The implications of managing tree canopies on root distribution and development, and its impact on soil stabilisation functions, are being determined for poplar (Douglas et al., 2010b) and willow (McIvor et al. 2010) in the southern North Island. It is possible that the density of managed conservation trees will need to be increased to achieve similar levels of effectiveness for erosion control as unmanaged trees.

Root growth of a range of poplar and willow germplasm and vegetative material (cuttings stakes, poles) is being determined at two sites – one near Palmerston North and the second near Gisborne on the east coast of the North Island. Growth after one year was determined in April/May 2010 by excavation (e.g. Marden and Phillips 2011) and further excavations are scheduled for 2011 and 2012.

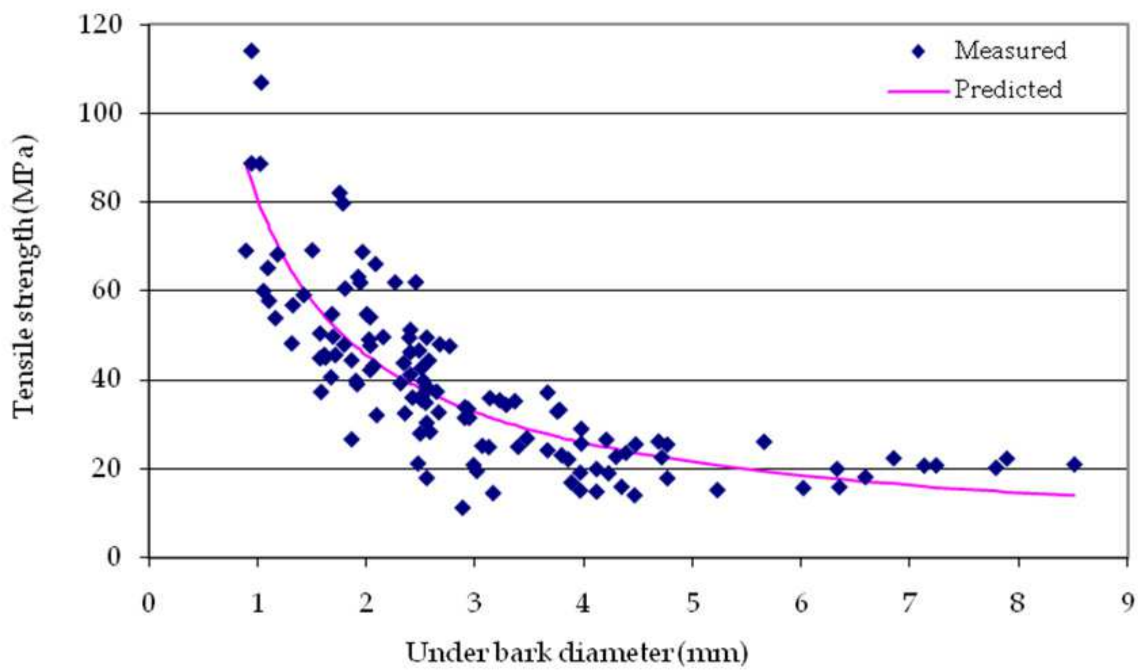

Fig. 5. Relationship between live root-wood tensile strength and under-bark root diameter for ‘Veronese’ poplar roots.

5. Modelling of hill country erosion and environmental outcomes

Effective programmes for controlling pastoral hill country soil erosion depend on close cooperation between the organisation responsible for environmental monitoring and protection and the landowner. The development of individual Whole Farm Plans (WFPs), incorporating physical, farm management and business plans, are designed to achieve sustainable land use, both environmental and economic. Whole farm plans also sit within a wider environment and have environmental outcomes at the catchment or greater level. This includes reduction in runoff and sediment entering waterways and river systems (the receiving environment), with consequent decrease in nutrients, particularly N and P, and reduction of flood risk through stabilisation of river-bed levels.

An effective monitoring programme is necessary to measure and analyse the impact of the approach at both the farm and broader scales. It will therefore have to provide information to the landowner for decision making and also be suitable for scaling up to the catchment scale. Monitoring to date of the effectiveness of WFPs has been largely limited to monitoring of the implementation of the conservation works programme, so that it has been generally activity based. Soil conservation activities include the planting of conservation poplar and willow trees at recommended densities/spacings, fencing off waterways, building sediment traps or wetlands along waterways, retiring steep land or planting it in forestry trees. Shifting the emphasis from actions/tasks to environmental outcomes will provide regional councils (see 2.1) with direct measures of the achievements towards the target goals. It will also indicate the rate at which progress is being made towards them, both at the WFP level and in larger areas of the region, through appropriate amalgamation of data from several or many WFPs.

Attributes that should be assessed or measured at any stage in the implementation of works in a WFP are:
i. vegetation type and cover (extent),
ii. the area of each works (at the individual site level), and
iii. age of vegetation.

These can all be assessed using aerial photography at an appropriate scale e.g. 1:3000 or (preferably) higher resolution, complemented with planting plans describing location and timing, and other knowledge of the farmer/land manager. Detection of areas of forestry, whether exotic or indigenous, is easier than those with spaced plantings of conservation trees on pasture, particularly when the trees are young, and field checking of sites is recommended e.g. for survival. Also, tree growth of the same species/clone can vary considerably with aspect, position on a slope, and other factors, so that knowledge of tree age is only a preliminary indication of the likely size of trees.

For conservation works involving forestry (exotic or indigenous), canopy cover can be estimated from appropriate aerial photographs, but a sequence over time e.g. every 3-5 years is required to make this a useful approach to determine critical times when effectiveness for erosion control (and sediment reduction) is increased significantly e.g. at canopy closure. Estimates of canopy cover per site with an accuracy of plus or minus 10% should be more than adequate to describe canopy development over time. Sites with spaced trees on slopes or in gullies are more difficult to assess for canopy cover because they almost always have lower and more variable tree densities than forestry. It is unwise to compare canopy covers of forestry with those of spaced trees because the same canopy cover in both vegetation systems will usually not indicate the same stand density - hence the implications for root distribution patterns and erosion control potential are quite different. For spaced trees, it is recommended that at least one measurement of tree size – dbh –is measured on a sample of trees at an individual site e.g. 1-5%, to complement data on tree age. This might be conducted on the same trees once every 3-5 years until tree maturity so that the task does not become overly onerous. Collection of such data will be useful to define tree size and will enable a better description of the status of trees which survive or die during future storms, and those which hold or fail to hold soil on eroded slopes.

5.1 Estimation of sediment export from farm with a whole farm plan

It is assumed that in the farm plan is well designed set of soil conservation works, including
i. Exotic afforestation
ii. Planting of spaced trees on pasture (2-tier farming; agroforestry, tree-pasture system)
iii. Regeneration of indigenous forestry (retired land from scrub to indigenous forestry).

5.1.1 Exotic forestry

Close-tree planting will reduce erosion on pastoral areas by 90% once trees are mature (Dymond *et al*., 2006). For trees less than 20 years old, a maturity factor may be defined by

$$M_f = Age_f / 20$$

where M_f is the maturity factor of forestry, and
Age_f is the age of the trees in years (for trees older than 20 years M_f is set to 1).
The long-term mean erosion rate is reduced by M_f x 0.9 for exotic forestry.

5.1.2 Spaced trees on pasture

If the pastoral land contains significant areas of highly erodible land (HEL), then there will be recommended soil conservation works as part of the WFP, designed to significantly reduce mass-movement erosion. The recommendations will involve

i. spaced tree planting, and
ii. gully tree planting.

It is assumed that these conservation works will reduce mass-movement erosion by 70% once plantings are mature ((Hawley and Dymond, 1988; Thompson and Luckman, 1993; Hicks, 1995). The maturity factor of the soil conservation works may be calculated by

$$M_p = f \times Age_p / 15$$

where M_p is maturity factor of the soil conservation trees,
f is the proportion of trees in the plan that have actually been planted, have survived, and are well maintained, and
Age_p is the age of the soil conservation trees (for trees older than 15 years Age_p is set to 15).
The long-term mean erosion rate is reduced by $M_p \times 0.7$ for spaced trees on pasture.

5.1.3 Indigenous forestry

Vegetation on retired land is assumed to be at one of five phases with maturity factor M_r:

i. reverting pasture; $M_r = 0.0$
ii. incomplete scrub canopy closure (early stage); $M_r = 0.1$
iii. incomplete scrub canopy closure (intermediate stage e.g. 3 years); $M_r = 0.5$
iv. complete scrub canopy closure; $M_r = 0.9$ (usually after 5 years), and
v. indigenous forest. $M_r = 1.0$

The long-term mean erosion rate is reduced by $M_r \times 0.9$ for indigenous forestry.

5.2 Calculation of sediment export from farm

For simplicity, it is assumed that all sediment lost from eroded land enters waterways and leaves the farm. However significant quantities of sediment may be retained on-farm through appropriate structures e.g. dams, or through natural means e.g. wetlands, but these are not considered here.

1. Sediment export (tonnes/yr) from land with **exotic forestry** is $e_f \times [1-M_f \times 0.9] \times A_f$

where e_f is the mean erosion rate (tonnes/km²/yr) of the exotic forestry land if it was in pasture (from NZeem®: Dymond et al., 2010) and
A_f is the area of exotic forestry in the farm plan (km²).

2. Sediment export (tonnes/yr) from land with **spaced trees** is $e_p \times [1-M_p \times 0.7] \times A_p$

where e_p is the mean erosion rate (tonnes/km²/yr) of the pastoral land with trees, if trees were not planted (from NZeem®), and
A_p is the area of land with trees on pasture in the farm plan (km²).

3. Sediment export (tonnes/yr) from land with **indigenous forestry** is $e_r \times [1-M_r \times 0.9] \times A_r$

where e_r is the mean erosion rate (tonnes/km²/yr) of the indigenous forestry land if it was in pasture (from NZeem®), and
A_r is the area of indigenous forestry in the farm plan (km²).
e_f, e_p *and* e_r may or may not be the same.
The **total sediment export** S (tonnes/yr), from a farm which contains land use/ conservation works with a range of maturities, may be calculated by estimating the mean

Case study Farm in hill country near Palmerston North, southern North Island

These formulae were applied to the Whole Farm Plan (WFP) for a commercial farm. According to NZeem® the farm currently exports 2640 tonnes of sediment per year on average. If the following soil conservation methods (from the WFP) were implemented

Year 1 - 200 space-planted poplars
Year 2 - Afforestation of 3.4 ha; 200 space-planted poplars
Year 3 - Afforestation of 8.6 ha; 130 space-planted poplars; 70 poplars for gully control
Year 4 - Afforestation of 12.0 ha; 130 space-planted poplars; 70 poplars for gully control
Year 5 – Afforestation of 6.6 ha; 200 space-planted poplars.

then the sediment export from the farm would reduce gradually from 2640 tonnes/yr to 820 tonnes/yr over 20 years.

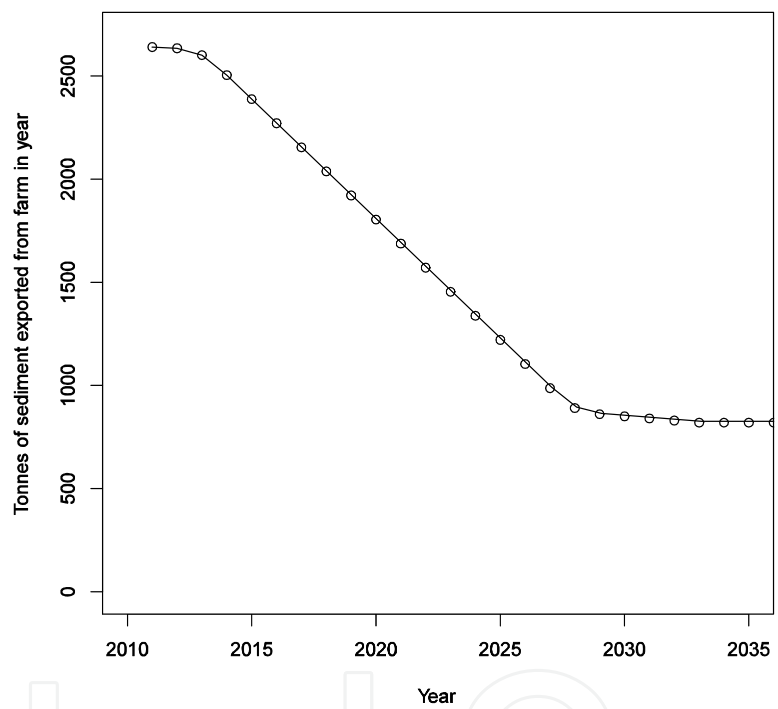

Fig. 6. Sediment export from hill country farm after implementing soil conservation works in the case study.

$S = e_f(1-0.9\bar{M}_f)A_f + e_p(1-0.7\bar{M}_p)A_p + e_r(1-0.9\bar{M}_r)A_r$ where $\bar{M}_f$ is the mean maturity factor for the exotic forestry sites, $\bar{M}_p$ is the mean maturity factor for the spaced tree sites, and $\bar{M}_r$ is the mean maturity factor for the indigenous forestry sites.In a WFP for a 20 yr period, for example, there may be three sites with exotic forestry planted in Yr 0, Yr 5 and Yr 15, 20 sites with spaced trees on pasture (annual plantings of 150 poles), and two sites where growth of indigenous vegetation is encouraged through retirement – the first in Yr 5 and the second in Yr 15. The formula can be applied at any stage of the implementation of the conservation works in a WFP ranging from entirely new, through partial implementation, to completed implementation. Therefore it can be applied to WFPs implemented already.

The case study (above, figure 6) shows how these formulae are applied to estimate the sediment export of the three major vegetation covers/land uses at sites within a farm.

6. Climate change and soil erosion in New Zealand pastoral hill country

Climate change will have measurable effects at the farm scale in our lifetimes, whether through pasture composition changes, increased productivity of some pastures, increased loss of productive soil from underprotected landscapes, a greater frequency of drought years or general changes in water availability. It is not clear at this stage where the balance between positive and negative impacts will lie. However, it appears very plausible that proactive adaptation to these changes will help landowners to shift the balance more towards the positive side of effects. Ongoing research will help address some of these issues and provide a better basis for informed decision-making.

There is an increasing need for collaboration between New Zealand scientists working on erosion rates, climate change scenarios, soil conservation methods, and sediment management as the problems become more complex. Coupled with this increased collaboration is the equally important requirement to communicate scientific findings to both policy makers and landowners.

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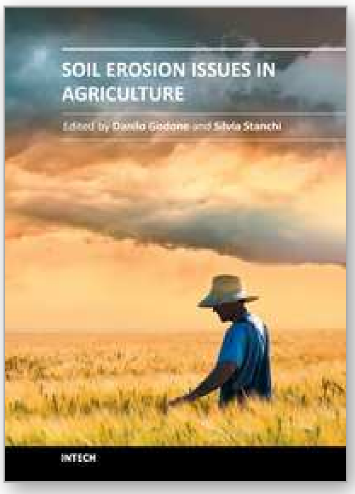

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