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Slopewash erosion following plantation harvesting in pumice terrain and its contribution to stream sedimentation, Pokairoa catchment, North Island, New Zealand

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Abstract

Post-harvest sediment generation by slopewash erosion was measured from sites of soil disturbance on hauler-logged areas in pumice terrain; Pokairoa catchment, Central North Island (38.19°S, 166.45°E), New Zealand. Slopewash and a storm-initiated landslide were the principal sediment-generating processes. Slopewash and vegetation recovery rates were measured at field plots on sites with shallow and deep disturbance, and a regression relationship was established between sediment loss (g day^{-1} mmrain^{-1} m^{-2}) and percent vegetation cover for both plot types. At the plot scale, in the first post-harvest year, deep-disturbance sites generated 85% of total slopewash produced from both disturbance sites combined. At 3.8 t ha^{-1}, this was ~5 times more than that generated from shallow-disturbance sites. In year 2, slopewash declined, with deep-disturbance plots generating 1.2 t ha^{-1}, twice that from shallow-disturbance plots. By 21 months, when groundcover occupied 80% of plot area, sediment generation had declined to almost zero.

At the scale of forest management areas (compartments), 75% of the total slopewash generated from both disturbance classes combined, during the 2-year post-harvest study period, was generated in the first post-harvest year. Of this, 63% was generated within the first 7 months following harvesting and before the application of desiccant. In the second post-harvest year further sediment loss from deep-disturbance sites was limited because most readily available sediment has already been removed, whereas the minimal decrease on uncompacted shallow-disturbance sites was more a function of infiltration rates exceeding rainfall than a consequence of site recolonisation. Rates of surface lowering on sites of shallow- and deep-disturbance on pumice terrain in Pokairoa differ by an order of magnitude.

The relative contribution of sediment delivered to the Poumako Stream by slopewash and landslides was highly dependent on their connectivity with stream channels. During the period of this study, a single storm-initiated landslide was the most important hillslope process, contributing the equivalent of ~6000 times more sediment to Poumako Stream than was delivered by slopewash from 38 ha (excluding roads and landings) of clearfelled forest.

Keywords

slopewash, sedimentation, forest harvesting, slope-channel connectivity, Central Volcanic Region, New Zealand.

Introduction

In recent years there has been a significant increase in forest harvest activity throughout New Zealand, much of it in areas originally planted in exotic forest for erosion control or because of poor and declining economic returns from pastoral farming. At the time the forests were established, many such areas were considered environmentally sensitive and vulnerable to human-induced disturbances during forest harvesting and/or by landsliding during storms. Concerns over a potential increase in stream sedimentation following the harvesting of an extensive area of plantation forest in the Central Volcanic region of the North Island (38.19°S, 166.45°E), New Zealand, led to the establishment of a multiple catchment study to monitor stream flow and sediment discharge from the Pokairoa Stream catchment, Northern Boundary, Kaingaroa Forest. Sediment from the Pokairoa catchment is discharged into Lake Aniwhenua (Fig. 1), where it is a potential threat to the long-term storage capacity of this lake.

Because of the historic planting pattern of Kaingaroa Forest, the current age-class harvesting schedule will see most of the Pokairoa catchment harvested within a decade. Small areas planted in the 1950s were harvested before this study, but as there were no hydrological records for the Pokairoa Stream and its tributaries before, during and after harvesting, it was not possible to attribute sediment production to forest harvesting activities or to specific rainfall events. A study was therefore initiated in mid-1993 to gather information on stream flow and sediment yield prior to and during the harvesting of the Pokairoa catchment. Numerous reports document the results of this work for the period 1993 to 1998 (Rowe, 1995; Rowe *et al.,* 1996; Rowe and Marden, 1996, 1997, 1998).

With the anticipated increase in stream flow as a function of harvesting, it was perceived that stream sediment yield would likely increase. This led to concerns about the identification of potential sediment sources and of the processes that could mobilise and transport sediment to stream channels. While most New Zealand studies on harvest-related impacts recognise the significance of roads, tracks and landings as sediment sources (Fahey and Coker, 1989, 1992; Mosley, 1980; Pearce and Hodgkiss, 1987; Smith and Fenton, 1993; Fransen, 1998), few have focussed on

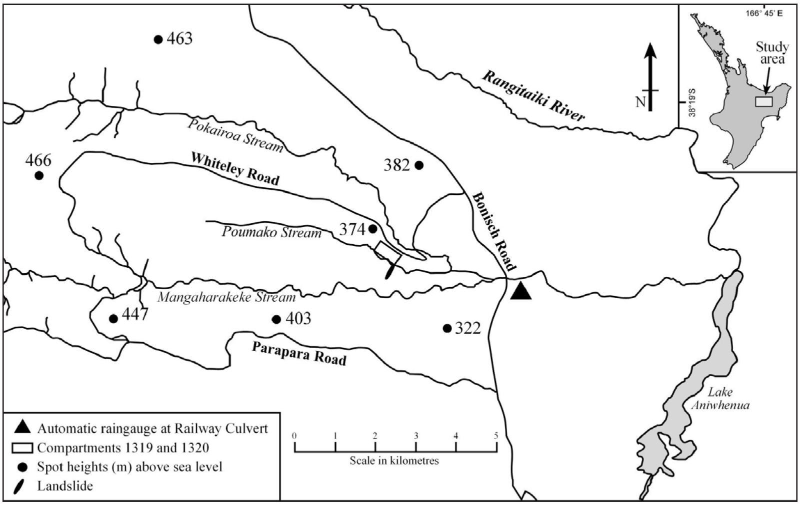

Figure 1 – Location map of study catchment within Pokairoa catchment.

quantifying the sediment-generation potential of sites of soil disturbance as a consequence of harvesting (Marden and Rowan, 1997; Fransen, 1998; Marden *et al.,* 2006). When disturbed, soil and its underlying cover beds (largely pumice) are considered to be highly mobile in this volcanic terrain. Sites disturbed as a consequence of harvesting are therefore a potential source of sediment that, once mobilised, could potentially enter a permanent water body and increase stream sediment yield.

In 1996, and as an adjunct to the stream sediment-monitoring programme, a new research project was initiated to quantify slopewash-derived sediment generation and mobility from sites disturbed following harvesting (excluding tracks, roads and landings). For undulating terrain dissected by ephemeral gullies and logged using ground-based methods, a semi-quantitative approach was used (Rowe *et al.,* 1996; Rowe and Marden, 1996). However, for harvested areas on steeper slopes and in proximity to permanently flowing streams, a more quantitative approach was adopted; an approach that would produce data comparable with previous studies undertaken on harvested sites in different lithologic terrains and similarly harvested using cable haulers (Marden and Rowan, 1997; Marden *et al.*, 2006).

In this paper we quantify the amount of pumiceous sediment derived by slopewash from sites disturbed by harvesting. We explore the relationship between sediment generation and groundcover vegetation recovery and sediment-travel distance during the immediate post-harvest period. In addition, and from an understanding of the proximity of disturbed sites relative to stream channels, we have attempted to quantify the amount of slopewash-derived sediment delivered to stream channels and hence its contribution to stream sediment yield. Sediment generated from roads and landings was not measured in this study.

We discuss the implications of this research for forest management in the Central Volcanic region of New Zealand.

Methods

Study area

The Pokairoa Stream catchment (1720 ha) consists of three major sub-catchments: Mangaharakeke Stream, Poumako Stream and Pokairoa Stream (38.19°S, 166.45°E). Pokairoa Stream rises on the northern edge of the Kaingaroa Plateau at about 425 m, and descends to about 150 m at Lake Aniwhenua (Fig. 1). The study site itself comprises compartments (forest management areas) 1319 and 1320 within the Poumako Stream sub-catchment (1002 ha) (Fig. 1). There the slopes are typically short, steep and weakly sinusoidal, and they drain directly into the Poumako Stream. In places, low, narrow and discontinuous depositional terraces occur at the base of slopes.

The Kaingaroa Plateau is formed from various ignimbrite sheets, including the Rangitaiki Ignimbrites and Matahina Ignimbrites of late Pleistocene age (NZ Geological Survey, 1974), overlain with several late Quaternary cover deposits (NZ Soil Bureau, 1960) mostly air-fall tephras (Pullar and Birrell, 1973). The tephras include air fall from the Taupo (c.1850 years BP), Kaharoa (c.770 years BP), and Tarawera (c.104 years BP) eruptions. Here the Tarawera and Kaharoa deposits are both typically between 50 mm and 400 mm thick. The total thickness of pyroclastic cover deposits is about 6 m (Pullar and Birrell, 1973). The soils are young, granular, permeable, buried airfall-pumice described as Tephric Recent Soil (Hewitt, 1998). The gravelly topsoil formed on Tarawera lapilli has little humus and has accumulated only 0.71% carbon and 0.07% nitrogen since its deposition. The

C/N ratio of 11 for Tarawera gravel is low; available phosphorous is also low, but pH is high (7.2) (Vucetich and Wells, 1978). The subsoils (e.g., Tarawera gravel) consist of vesicular basalt lapilli with few external signs of weathering. The particle size distribution approximates 68% gravel, 30% sand, and 2% silt and clay (Mc Queen *et al.*, 1991). Because of poor soil fertility and moisture retention, and low humus content, pasture is difficult to maintain, thus Tarawera gravel is better suited to growing exotic trees (Gibbs *et al.*, 1968).

Surface erosion processes, including rilling, gullying and slopewash erosion, are often a response to land management activities (Wallis and McMahon, 1994) and tend to be associated with periods of higher intensity rainfall (Healy, 1967).

Cut banks within dry gullies show evidence of erosion debris inter-layered with well-developed soils, indicating a cyclical pattern of surface erosion separated by long periods of stability. There were no historical mass movement features within the study site, although one landslide occurred on the slope opposite the study site (Fig. 1). It likely failed on 3 March 1996 (24-hour rainfall of 62 mm, return period of ~1 year), coinciding with an earlier phase of harvesting (Rowe and Marden, 1998).

The climate is temperate, with a mean annual rainfall at the nearest long term meteorological station, Kaingaroa Forest, of 1483 mm. Rainfall follows a slightly seasonal pattern, with more rain in the winter months (NZ Meteorological Service, 1980). Although the average annual rainfall is not high, rain often falls during short-duration, high-intensity storms in summer. Most of these events are localised and have important implications for erosion. A short-term rainfall record at Railway Culvert (Figs. 1 and 4) shows that for the period of study (August 1996-May 1998) there was only one day during which very heavy rain fell (105 mm on May 1997), although falls of 64 mm in December 1996 and 61 and 60 mm in June 1997 were recorded. The highest rainfall recorded for the period mid-1997 to mid-1998 was 48 mm in April 1998.

The predominant vegetation in Pokairoa catchment is exotic radiata pine (*Pinus radiata* D. Don), with minor amounts of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), planted in the early 1960s. The age-class distribution will see most of the radiata pine clearfelled within a decade of the beginning of harvesting, with areas of Douglas fir managed on a longer rotation (Coker *et al.*, 1990).

Landings were constructed in the study compartments in 1995, and harvesting with cable haulers was completed by July the following year. Between rotations, cutover is generally aerially desiccated using chemical spray to control the regeneration of indigenous and exotic groundcover species, including wilding (self-seeded) pines, and then replanted. Desiccant was applied in early April 1997 and in mid-April the cutover was oversown with a mixture of introduced grasses and legumes to minimise surface erosion. Compartments were replanted in radiata pine in June 1997.

Site selection, soil disturbance, sediment generation

Site selection was dictated by the availability of newly harvested compartments. With an initial goal of quantifying slopewash sediment generation and the influence of groundcover vegetation on sediment generation over time at the plot scale, we selected the most recently harvested part of compartments 1319 and 1320 (Figs. 1 and 2) in which to install sediment traps.

Sites of deep and shallow disturbance (Table 1), as potential sites of sediment generation, were identified by ground inspection. These sites are typically fragmented, small in extent, and occur at

Figure 2 – Aerial view of hauler-logged compartments 1319 and 1320 taken seven months after the completion of harvesting and before the aerial application of desiccant. Vegetation cover is regenerating indigenous shrubby hardwood species. The approximate location of 9 of the 10 sediment troughs is shown. Poumako Stream is on the left, and stream flow is west to east from the top of the photograph. Note the absence of accumulated bedload sediment in the Poumako Stream channel and the lack of sites of active streambank scouring and of surface disturbance attributable to harvest activities.

points of slope inflexion. Mean slope angle was 30° (range 18–35°) and 32° (range 25–38°) for shallow- and deep-disturbance plots, respectively. As our aim was to measure slopewash, we avoided haul-paths and tailored the dimensions of our plots to the size of available sites where slopewash was likely to be the dominant process.

Sediment generation at the plot scale was measured using 3 m × 3 m plots bounded with wooden sides to prevent sediment from slopes adjacent and above entering the 'catch-trench' (0.5 m × 3 m) at the down-slope end. The catch-trench was lined with semi-porous roading fabric, allowing surface runoff to dissipate while trapping all but the finest suspended sediment fraction. The 'tide marks' preserved on the fabric indicated that for the duration of the measurement period none of the catch trenches were overtopped.

Five plots were located on sites of shallow disturbance and another 5 on sites of deep disturbance (Fig. 2). To assess the mobility of material disturbed as a consequence of logging

Table 1 – Description of site disturbance classes.

Site disturbance class	Description
1. Undisturbed	Ground cover vegetation flattened but otherwise unaffected by logging operations; litter layer and topsoil intact
2. Shallow-disturbance	Some surviving grasses/weeds; needle litter removed or reworked, topsoil scarified but largely intact
3. Deep-disturbance	No surviving vegetation; surface soil removed to expose parent materials (e.g. colluvium or bedrock). In the literature these sites are also referred to as 'bare ground' or as 'exposed mineral soil' (EMS). These sites are created during the harvest period and are the result of the repeated 'dragging' of logs across slopes. The process of removing and distributing sediment from these sites at the time of logging is herein called 'soil scraping'. These same sites are subjected to slopewash during the post-harvest period and are a source of additional sediment.

Figure 3 – Sediment trough located on a site showing signs of deep disturbance as a consequence of harvesting. **a**) photo taken immediately following the completion of harvesting, **b**) 12 months after desiccation. The log haul direction is from the bottom of the trough to the top. Short pegs within the bounded trough were used to assess percent groundcover per sub-plot over time.

and its potential transportability to a stream channel, we located one of the troughs downslope of a 'slug' of freshly disturbed pumice within ~10 m of the Poumako Stream channel. To allow sediment from the 'slug', if mobilised, to move through the plot and into the fabric-lined catch trench at its downslope end, a distance of 5 m, the uphill end of this trough was not bounded.

Slopewash sediment was collected approximately monthly over a 21-month period between August 1996 and May 1998, and sediment generation rates (g m^{-2}) were calculated from the weight of oven-dried sediment (Table 2). Samples were then dry-sieved to determine the particle size distribution of sediment mobilised by slopewash. Organic matter (pine needles and twigs) was separated from the samples prior to drying and weighing, and discarded.

Table 2 – Plot-scale and compartment-scale sediment generation rates and volumes for compartments 1319 and 1320 over a 2-yr post-harvest period.

Time after clearfelling:	**1st post-harvest year**		**2nd post-harvest year^{A} (8 months)**	
Disturbance:	Shallow	Deep	Shallow	Deep
Plot-scale sediment generation				
	(n = 5)	(n = 5)	(n = 5)	(n = 5)
Total plot sediment weight (kg) (% of total of period monitored)	3.1 (15%)	16.9 (85%)	1.3 (26%)	3.7 (74%)
Sediment generation rate (t/ha/year) (s.e. values are in parentheses)	0.7 (0.29)	3.8 (1.29)	0.5 (0.24)	1.2 (0.75)
Compartment-scale sediment generation^{B}				
	(15.3ha)	(2ha)	(15.3ha)	(2ha)
Sediment generated (t) & % of period total	10.7 (59%)	7.5 (41%)	4.4 (73%)	1.6 (27%)
Total sediment	18 (75%)		6 (25%)	
2-year sediment total (t)				
Sites combined	24			
Shallow-disturbance	15.1			
Deep-disturbance	9.1			

[A] Note: Sample period for the second post-harvest year spanned 8 months. The rate of sediment generation (tonnes ha^{-1} yr^{-1}) presented for year 2 has been annualised.

[B] compartment-scale sediment values have been calculated from plot-scale rates (tonnes ha^{-1}) multiplied by the area of disturbance.

Sediment data were analysed using repeated measures ANOVA in the GENSTAT 6.2 (2002) statistical package. F-tests obtained from the ANOVAs were used to compare sedimentation rates (Sokal and Rohlf, 1995). Rates of sediment generation were standardised to grams per m^2 of contributing area per mm rainfall per day (g m^{-2} mm rain^{-2} day^{-1}) and annualised. Rainfall was measured with a 0.5 mm resolution tipping-bucket rain gauge at 15-minute intervals. This gauge, with a 200-mm diameter orifice, was located at Railway Culvert (Fig. 1) at an elevation of 220 m above sea level.

To calculate sediment generation (t ha^{-1} year^{-1}) at the compartment scale, we applied the annual plot-based rates of slopewash-generated sediment for deep- and shallow-disturbance troughs to the summed area of like-disturbance within compartments 1319 and 1320 (Table 2). The summed area of each disturbance class was measured from aerial photography (flown in April 1997) using a dot grid. Roads and landings were delineated on the photographs using a fine-nibbed mapping pen and measured with a digital planimeter. The aerial photography fortuitously captured the occurrence of a landslide initiated in March 1996, soon after the completion of harvesting. Although this landslide occurs on the slope opposite our study compartment s (Fig. 1), the sediment generated by it entered Poumako Stream. We therefore took this opportunity to document the relative amounts of sediment generated and delivered to Poumako Stream by these two contrasting processes. The location (proximity and connectivity to Poumako Stream) and size of the landslide were measured directly from aerial photographs using a dot grid. The volume of sediment mobilised by the landslide (m^3) was based on a mean field-depth (1 m) of the source zone.

Surface lowering, particle size analysis and sediment delivery to streams

Surface lowering (mm yr^{-1}) was calculated using a mean bulk density of 1.70 g cm^{-3} (Rowe and Marden, 1997).

To determine the particle size range able to be transported by slopewash, on seven occasions throughout the 21-month sampling period we sieved the bulked monthly samples collected from all troughs. The particle size data presented are the mean value of seven sievings.

The relative contribution of sediment delivered to Poumako Stream from areas affected by slopewash and by the one landslide was assessed, based on the 'connectivity' of these sites with the stream channel. Figure 2 shows the position of the plots relative to stream channels. Connectivity was determined from the aerial photographs. Only two deep-disturbance sites and one landslide were directly coupled to the Poumako Stream. These often-compacted sites were essentially devoid of loose material and, because of their proximity (on the stream bank) and direct connectivity with Poumako Stream, it was assumed that almost all sediment derived from these sites would be delivered directly to the stream channel. This occurred at the time of logging. We therefore adopted a sediment delivery to streams (SD) value of 100% for material derived from their combined surface area. For the landslide, field-based measurements (depth of the 'source zone' and length and thickness of the 'debris trail' deposit) indicated approximately half the material generated at the time of landslide initiation was retained on-slope and half was delivered to the stream (i.e., an SD of 50%).

The connectivity of shallow-disturbance sites to streams could not be established by examining aerial photographs. However, from our plot studies it was apparent that slopewash on these sites was capable of mobilising and transporting sediment downslope to the catch trench, a distance of 3 m. In addition, from observations made at the open-ended trough, we confirmed that sediment could be transported for a distance of 5 m, but that it was unlikely for sediment produced from these essentially non-compacted sites to travel further than 10 metres downslope of its point of origin, being instead trapped by vegetation and logging slash, and in microtopographic hollows. Also, the concave-shaped toe slopes and, in places, alluvial terrace remnants adjacent to the Poumako Stream, further diminished the potential travel distance of sediment and therefore its likelihood of reaching the stream channel. With such small volumes of sediment generated from shallow-disturbance sites (Table 2), in combination with rapid post-harvest recovery of groundcover vegetation, we considered the amount of sediment generated and mobilised from within a 10-m wide corridor adjacent to the Poumako Stream and delivered to the channel would be minute and no sediment generated beyond this distance would reach the channel.

Vegetation recovery

The application of aerial desiccant followed by oversowing is common practice in most plantation forests throughout New Zealand. Groundcover vegetation was assessed within the 3 m × 3 m sediment plots, before and following desiccation, using the 'abundance/sociability' technique of Braun-Blanquet (1932, 1965). This technique involved subdividing each deep- and shallow-disturbance plot into nine 1-m^2 subplots and visually recording the percentage of groundcover in each corner and in the central subplot (i.e., 5 subplots) to derive a monthly mean measure of groundcover extent. Ground-based photographs of the plots were taken at the time of sediment collection (Fig. 3). At the plot scale, the response of groundcover vegetation to harvest (a consequence of hauler logging) and post-harvest (desiccation and oversowing) forest practices is expressed as mean percent cover over time (months since the completion of harvesting). A Mann-Whitney U host test (Siegel and Castellan, 1988) was used to examine differences in vegetation cover and recovery between deep- and shallow-disturbance sites. The regression procedure in GENSTAT (2002) was used to analyse the relationship between percent vegetation cover and sediment generation rate. The null hypothesis of zero slopes in these regressions was tested using t-tests (Sokal and Rohlf, 1995).

Results

Site disturbance

Hauler logging resulted in 2 hectares of deep-disturbance, 5% of the combined area of compartments 1319 and 1320. Across the remainder of the study compartments, 38% (15.3 ha) was subjected to shallow disturbance, 52% (20.7 ha) constituted non-sediment-generating sites (undisturbed, slash cover, rocks and stumps) and 5% (2 ha) was roads and landings. Although located outside of the study compartments, the one landslide (source area only) occupied the equivalent of < 1% (0.03 ha) of the combined harvested area.

Post-harvest sediment generation, surface lowering and delivery to streams

For the duration of the study period there was no consistent relationship between slopewash and daily rainfall. Nonetheless, the flux of slopewash generated in March 1997, one month before the application of desiccant (7-months after harvesting), was in response to a daily rainfall total of 54 mm (Fig. 4).

There was only weak evidence for lower sediment generation rates on shallow-disturbance sites than on deep-disturbance sites ($F_{1, 8} = 4.30$, $p = 0.07$) but sediment generation rates differed significantly with

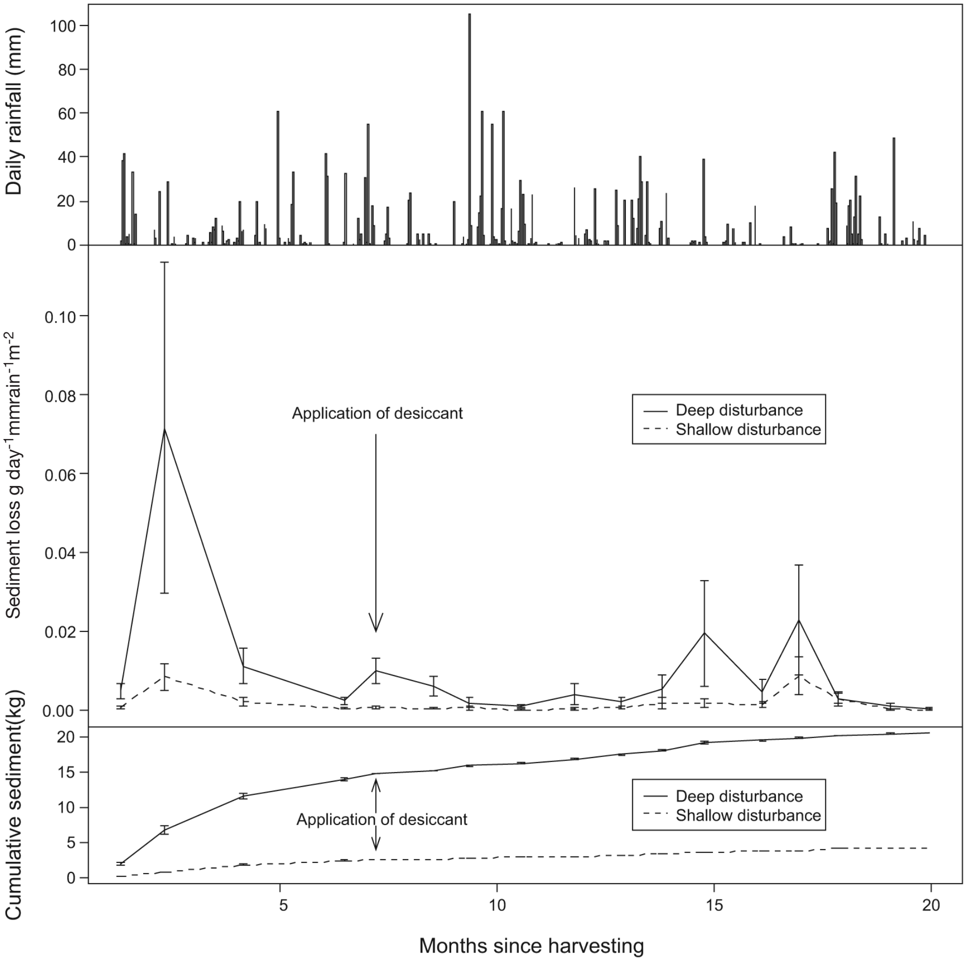

Figure 4 – Contrasting rates of sediment loss from shallow- and deep-disturbance sites over a 21-month (August 1996-May 1998) post-harvest period. Error bars are ± 1 SE.

time since harvesting ($F_{16, 124}$, = 1.88, p = 0.03) (Fig. 4, Table 1).

The regression analysis of the relationship between the rate of slopewash generation and percent vegetation cover was not significant on either shallow-disturbance sites (t_{15} =0.37, p = 0.72) (Fig. 5) or deep-disturbance sites (t_{15} =-0.81, p = 0.43) (Fig. 6).

In the first post-harvest year, deep-disturbance sites generated 85% of total slopewash produced from both disturbance sites combined. At 3.8 t ha^{-1} (tonnes rounded), this was ~5 times more than that generated from shallow-disturbance sites (Table 2). In the second post-harvest year, sediment generated from these plots declined, with deep-disturbance plots generating 1.2 t ha^{-1}, twice that from shallow-disturbance plots. By 21-months, by which time groundcover occupied 80% of both plot areas (Fig. 7), sediment generation had declined to almost zero.

Compartment-scale measurements show that, of the total slopewash generated from both disturbance classes combined during the 2-year post-harvest period (24 t), 75% was

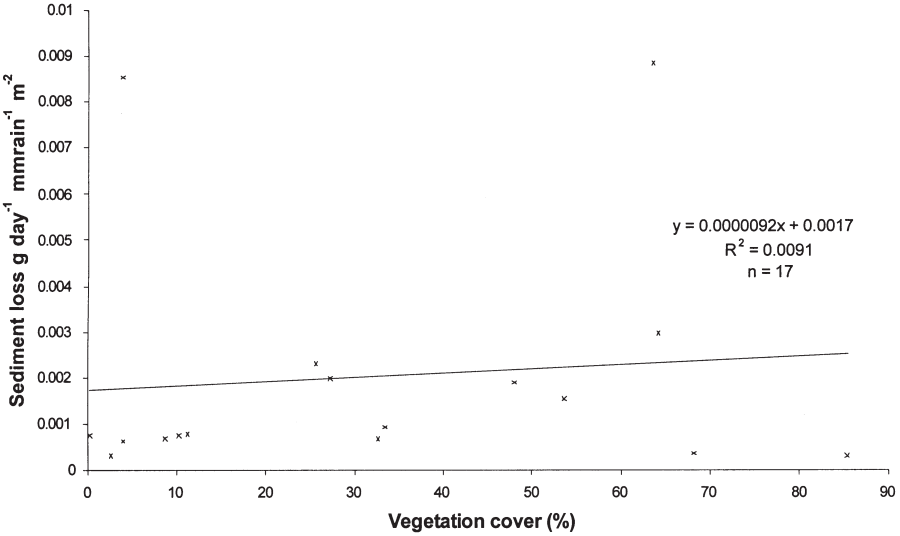

Figure 5 – Plot-scale regression analysis of the relationship between sediment loss by slopewash and percent vegetation cover on shallow-disturbance sites.

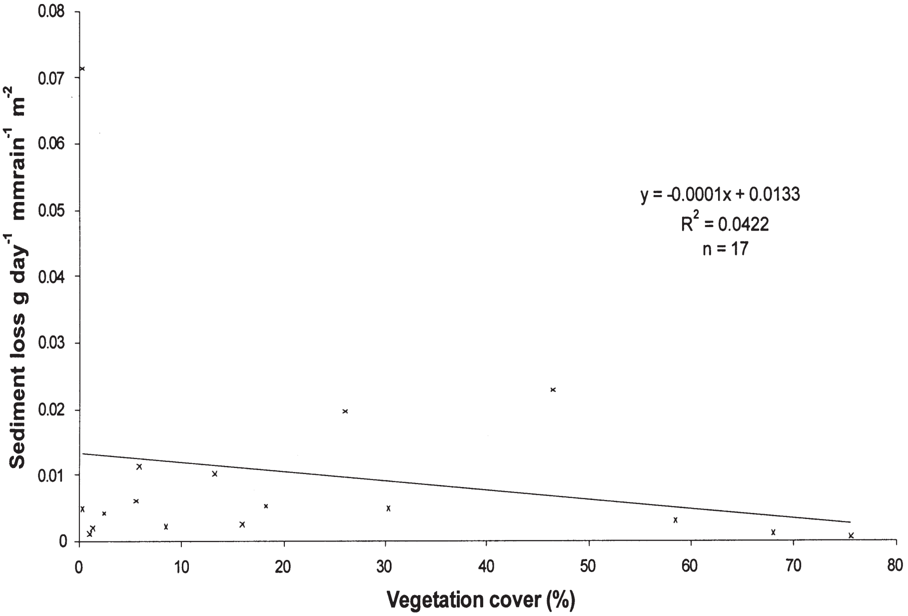

Figure 6 – Plot-scale regression analysis of the relationship between sediment loss by slopewash and percent vegetation cover on deep-disturbance sites.

generated in the first post-harvest year. Of this, 63% was generated within the first 7 months following the completion of harvesting and before the application of desiccant (Fig. 4). In addition, even though slopewash generation at the plot scale was significantly greater from deep-disturbance sites, at the compartment scale, sites of shallow-disturbance generated 60% (~15 t) of the 2-year total from both sites combined (24 t) (Table 2).

Particle-size analysis of sediment collected monthly from troughs over the 20-month study period showed that particles in the gravel range (>2 mm) predominated (71.5%), while silt and sand-sized particles (<2 mm) comprised 28.5%. The maximum particle size of pumice fragments was 20 mm.

Surface lowering by slopewash was an order of magnitude greater on sites of deep disturbance (~-0.3 mm) than on sites of shallow disturbance (<-0.1 mm) over the 2-year post-harvest period.

The amount of slopewash-derived sediment from shallow-disturbance sites that reached the stream channels proved too difficult to measure. The low sediment-generating potential of these sites, together with their low frequency of stream-connectivity (Fig. 2), ensured sediment delivery to streams was restricted. In addition, the high porosity and permeability of the pumiceous soil and the spatially fragmented distribution of disturbed sites, together with a heavy slash cover and the rapid recolonisation by ground cover vegetation, also restricted sediment supply to streams. Thus most, if not all, of the ~15 t of sediment generated from these sites (Table 2) was retained on slope.

Two deep-disturbance sites were coupled to Poumako Stream, from which 15 kg of sediment was delivered to the stream channel. This represents ~0.2% of the total sediment generated from sites of deep disturbance across the entire logged area.

Of the 176 t of sediment generated by the landslide, it is estimated that ~88 t was delivered to Poumako Stream at the time of landslide initiation (Table 3).

Table 3 – Process-based sediment generation and percent of total sediment delivered to streams from connected sites over a 2-year, post-harvest period, Pokairoa Forest.

Process	Sediment generating site	Area connected to stream (ha)	Sediment generated (t)	Sediment delivered to stream (t)	Percent of total
Slopewash	Shallow disturbance	n/a	n/a	n/a	n/a
	Deep disturbance	0.003	0.015	0.015	0.1
Landsliding	Landslides source area (n=1)	0.03	176	88*	99.9
Totals	All sources	0.033	176.015	88.015	100

Percent of total sediment delivered to permanent stream channels has been rounded. * 50% of sediment generated by 1 landslide is estimated to have remained on-slope as 'debris-trail' and levee deposits. n/a = not assessed (believed to be negligible).

Post-harvest vegetation recovery

Immediately following harvesting, groundcover vegetation occupied about 1% of the logged area (Fig. 7). During the early post-harvest period the rate at which groundcover vegetation recolonised sites was closely related to the degree of site disturbance, and differed significantly between sites of deep and shallow disturbance ($U_{13,\,13} = 34$, $p = 0.009$), irrespective of site preparation treatments, i.e., before replanting. Initial recovery was quickest on areas of shallow disturbance,

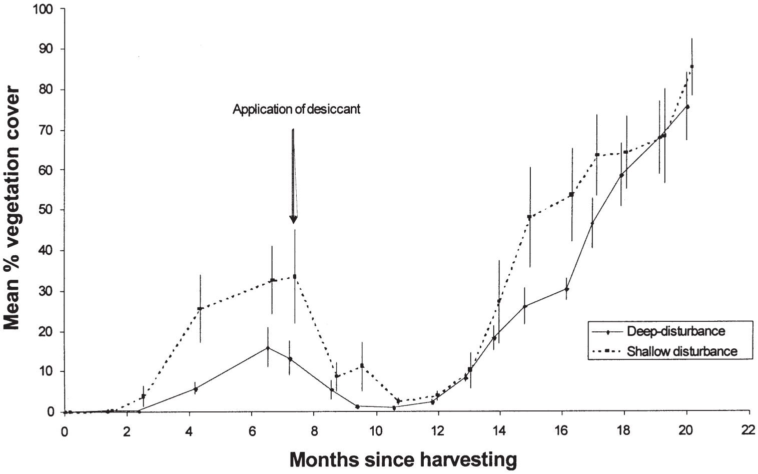

Figure 7 – Plot-scale vegetation cover following harvesting showing the effect of the application of desiccant and subsequent oversowing on vegetation recovery over a 21-month (August 1996-May 1998) post-harvest period. Error bars are ± 1 SE.

peaking 7 months after the completion of harvesting and before desiccation, to occupy 33% of plot area, but only 16% of deep-disturbance plots. Indigenous shrubby hardwood species dominated at this time. These included *Senecio bipinnatisectus* (Australian fireweed), *Cirsium vulgare* (Scotch thistle), *Verbascum thapsus* (woolly mullein), *Pteridium esculentum* (bracken), *Conyza canadensis* (fleabane) and *Asplenium polyodon* (fern).

The aerial application of desiccant had its greatest effect on sites of shallow-disturbance, with groundcover declining to 3% of plot area within 3 months of the application of desiccant; on deep-disturbance plots groundcover occupied just 1% (Fig. 7). Desiccation therefore effectively reduced the groundcover by 94 % and 91% of the respective plot areas. During the following 4-month spring period, groundcover vegetation surpassed pre-desiccation coverage on the respective plots. Oversown grasses dominated but, in places, surviving native groundcover species made up a significant proportion of the total ground cover across both disturbance classes. Within 21 months of the completion of harvesting, groundcover vegetation had increased to ~80% on both disturbance sites (Fig. 7).

Discussion

In New Zealand, where harvesting of the predominant species radiata pine occurs at least once every 27–30 years, slopewash erosion and landsliding are basic processes common to all plantation forests. The extent of deep-disturbance sites in the Pokairoa Catchment as a consequence of hauler logging is less than that found in other similarly logged steepland forests elsewhere in New Zealand. Two independent surveys, undertaken in the Mangatu Forest, East Coast, North Island, recorded deep disturbance at around 12% (McMahon, 1995; Marden and Rowan, 1997). Comparable overseas studies, including that by Dyrness (1965), found that deep disturbance directly attributable to logging occupied 9% of the area harvested using a high-lead system.

In addition Wooldridge (1960) established that 11.5% of the area harvested using a skyline system was disturbed, while Garrison and Rummell (1951) found that mineral soil was exposed over 15.2% of the total area harvested by cable logging assessed in their study. Our results show that the extent of deep disturbance attributable to hauler logging in the Pokairoa catchment (5%), was considerably less than that found for similarly logged forests in New Zealand because: a) short, steep slopes allow log lift over much of the haul length; b) harvested areas were small and thus fewer log hauls crossed the same ground; and c) logs were hauled away from the stream channel and not across it, thereby significantly reducing the amount of stream bank disturbance.

The slopewash component of fluvial sediment budgets has seldom been measured on forest cutover in New Zealand. Although there was no consistent relationship between slopewash and total monthly rainfall, the flux of slopewash-derived sediment six months after the completion of harvesting (March 1997) (Fig. 4) was in response to a specific rainfall event during which rilling occurred on deep-disturbance sites. Rilling was responsible for generating most of the sediment from deep-disturbance sites, particularly during the early part of the first post-harvest year, i.e., before desiccation. As a consequence of the repeated dragging of logs across these sites, compaction caused a reduction in infiltration rates and conversely resulted in increased down-slope runoff along depressions formed by dragging log butt ends. At the plot scale, rilling was shallow and undoubtedly restricted by the short plot length. As many sites of deep disturbance are also of limited length (excluding haul-paths) and spatially discontinuous, rilling at the compartment scale is similarly constrained. Rilling was absent on non-compacted shallow-disturbance sites, where pre-harvest infiltration rates were unaffected by harvesting.

Slopewash is an unimportant sediment transport mechanism on the 90% of the hauler-logged setting that was classed as undisturbed or as shallow disturbance; there litter and ground cover vegetation effectively reduced the tendency for rainsplash to detach and mobilise soil particles. In addition, infiltration rates on these uncompacted sites generally exceed maximum rainfall intensities (e.g., in pumiceous terrain, Dons (1987) reports infiltration capacities of 225 mm/hr for pine forests), ensuring that overland flow and erosion of the soil surface rarely occurs. At the compartment scale and by the second post-harvest year, the spread of vegetation by seedling recruitment and encroachment around the perimeter of sites of shallow disturbance effectively reduced slopewash by 59% (Table 2). At the plot scale, however, the regression analysis of the relationship between the rate of slopewash generation and percent vegetation cover on shallow-disturbance sites was non-significant (Fig. 5), suggesting that infiltration rates rather than vegetation cover had the greater influence on sediment generation and mobility during the early post-harvest period.

In contrast, slopewash generation on sites of deep disturbance was not constrained by the presence of vegetation during the immediate post-harvest period, hence the regression analysis, though negative, was non-significant (Fig. 6). That is, the recolonisation of these sites was too slow to effect a significant reduction in sediment production. Furthermore, the tempo of slopewash activity did not increase following desiccation, indicating slopewash had already removed the bulk of the mechanically disturbed sediment during the pre-desiccation period. The conclusion drawn is that groundcover establishment, whether indigenous or exotic, is not sufficiently rapid during the first post-harvest year to prevent or slow slopewash erosion on deep-disturbance sites. It therefore follows that the practice of desiccating any existing groundcover vegetation before replanting has little influence on the amount or rate of sediment generation by slopewash during the early post-harvest period.

Nonetheless, we attribute the eventual reduction in area of deep-disturbance sites to the incremental spread of groundcover vegetation from the surrounding less-disturbed sites where vegetation established quickest. We conclude that the practice of oversowing, in the wake of desiccating the indigenous groundcover species, undoubtedly accelerates the recolonisation process during the post-desiccation period, thereby reducing raindrop impact, increasing transpiration and infiltration, and impeding overland flow to effect an ~80% reduction in slopewash erosion to near pre-harvest levels, at the compartment scale, within about two years of the completion of harvesting.

The initially slower rate of vegetation recovery during the first post-harvest year on deep-disturbance sites, compared with shallow and un-disturbed sites at Pokairoa, is also typical of hauler-logged sites elsewhere in New Zealand (Marden and Rowan, 1997; Rowe and Marden, 1998; Fransen, 1998; Marden *et al.,* 2006). As elsewhere, weed species dominated sites of deep disturbance, while grasses (*Yorkshire fog, Punawai browntop*), legumes (*White clover, Birdsfoot trefoil*) and indigenous shrubby hardwoods favoured sites where disturbance had been shallow. Recolonisation of areas in each disturbance class occurred at a similar rate during both the period before desiccation (by indigenous species) and also following spring germination (by oversown exotic species). Both species mixes therefore potentially attained a similar level of surface coverage and effectiveness against slopewash in an equivalent time (Fig. 7). However, unlike other areas, the rate of groundcover vegetation recovery during the second post-harvest year was greater at Pokairoa, reaching 80% for both site disturbance classes within two years of the completion of harvesting. This is attributed to the lesser degree of overall ground disturbance and in particular to the initial, significantly smaller extent of deep-disturbance sites.

On deep-disturbance sites in this pumiceous terrain, surface lowering by slopewash (-0.3 mm) is an order of magnitude less than in four other North Island forests (-6 to 10 mm) (Marden and Rowan, 1997; Fransen, 1998) where fractured sedimentary sandstone/mudstone lithologies predominate, and an order of magnitude less than for deeply weathered volcanics (-1.1 mm) at Whangapoua Forest, Coromandel Peninsula (Marden *et al.*, 2006). These differences may be explained as a combination of factors that predispose some lithologies, more so than others, to weathering and slopewash. For example, the greater surface-lowering rate associated with some soft-rock sedimentary lithologies is likely due to the presence of internal fracturing, joints and cleavage. Weathering thus causes these rocks to exfoliate into increasingly finer grain sizes that can be readily dislodged and transported by rainsplash and slopewash. By comparison, at Pokairoa, the overall lower rate of surface lowering on both deep- and shallow-disturbed sites is attributable to the very high permeability and porosity of the pumiceous parent materials, thereby limiting its mobility by slopewash processes (Rowe and Marden, 1998).

The high proportion (79%) of particle sizes in the gravel size range (> 2 mm) mobilised following harvesting suggests that mechanical disturbance occurred to a depth of ~10 cm, exposing the underlying coarse-grained Tarawera lapilli. Unlike other North Island forests where thin coverbed materials overlie impermeable bedrock and where the depth of mechanical disturbance has a significant effect on sediment generation rates, the slopes at Pokairoa are mantled with thick pyroclastic and permeable coverbeds up to 6 m deep. Hence, in the absence of compaction during mechanical disturbance, the depth of disturbance has little effect on sediment generation rates.

In this study, of the total sediment generated by slopewash (24 t, shallow-and deep-disturbance sites combined) and a landslide (176 t), slopewash was the less significant of the two processes (Table 3). In addition, as most of the slopewash-derived sediment originated from sites located high on the slope profile, far removed from stream channels (Fig 2), and as it comprised < 1% of the total amount of sediment delivered to the Poumako Stream, we conclude that slopewash was the least important process by which sediment was generated and delivered to streams within this forest harvest setting. That is, the relatively small contribution of sediment delivered to the stream from these sources was highly dependant on their 'non-connectedness' with Poumako Stream. Elsewhere, the importance of the connectivity or linkage between sediment sources and the receiving waters has also been recognised as a factor in how much sediment is delivered to waterways (Novotny and Chesters, 1989; Croke and Mockler, 2001). Of the sediment delivered to the Poumako Stream, a single storm-initiated landslide was the single most important hillslope process and contributed the equivalent of ~6000 times more sediment than was delivered by slopewash from 38 ha (excluding roads and landings) of clearfelled forest. Apart from minor erosional breaks, the ubiquitous presence of air-fall slope deposits suggest that landslide failure is not a common occurrence in this terrain but, interestingly, the one landslide recorded in this study was likely triggered during a rainfall event with a return period of ~1 year.

Conclusions

The results of this study show the extent of deep-disturbance attributable to hauler logging in the Pokairoa Catchment and is in keeping with findings from several international studies of forestry practices that involve heavy machinery. While it did not exceed that found in other studies, the extent of deep disturbance was about half that found in similarly logged forests in New Zealand. These studies all show that the removal of slash and soil litter to expose the underlying mineral soil results in a substantial increase in slopewash-generated sediment. Also, slopewash erosion on harvested slopes is highly discontinuous, both spatially and temporally, with much of the mobilised sediment being trapped and stored on-slope and thus not reaching stream channels. On deep-disturbance sites, the conclusion drawn is that groundcover establishment during the immediate post-harvest period, whether indigenous or exotic, is not sufficiently rapid to prevent or slow slopewash erosion. It therefore follows that the practice of desiccating existing groundcover vegetation before replanting had little influence on the production of slopewash sediment during this period. In addition, the practice of oversowing, in the wake of desiccating the indigenous groundcover species, undoubtedly accelerated the recolonisation process during the post-desiccation period, thereby reducing raindrop impact, increasing transpiration and infiltration, and impeding overland flow to effect a ~50% reduction in slopewash erosion. We nonetheless attribute the reduction in area of deep-disturbance sites in the longer term (years), to the incremental spread of groundcover vegetation from the surrounding less-disturbed sites where vegetation established quickest.

The relative contribution of sediment delivered to the Poumako Stream by slopewash and landslides was highly dependant on their connectivity with stream channels. Of the amount of sediment delivered to the Poumako Stream during the period of this study, a single storm-initiated landslide was the single most important hillslope process and slopewash was the least important.

Implications for forest management

For forest environments, more effort has been devoted nationally and internationally to reducing slopewash than to any other form of erosion because it is the most easily controlled. The results of this and other studies, however, show that slopewash is the least important of the erosion types found in a forested setting (excluding roads and landings) and a relatively minor contributor of sediment to streams.

Although the erosion rate attributable solely to harvest practice is not considered severe, further reductions could be accomplished by reducing mechanical site disturbance in the vicinity of stream channels. Very deep disturbance to expose the mineral soil should therefore be kept to as a low a proportion of total disturbance as possible. Riparian areas of existing or re-established vegetation have been promoted as an effective means of reducing the delivery of slopewash-generated sediment to streams. They are intended to reduce both raindrop impact and the energy of surface slopewash, and to provide a root network to bind individual soil particles in place. In the absence of mechanical ground disturbance adjacent to streams and the preservation of intact ground cover vegetation, slopewash-transported sediment may be effectively filtered out and is unlikely to enter streams in amounts that could be considered significant. In contrast, riparian vegetation tends to be largely ineffective in preventing the much larger mass of landslide-generated debris from entering streams.

This study has shown that sediment generated from either sites of deep or shallow disturbance on hauler-logged slopes has not contributed in a significant way to the documented post-harvest increase in stream sediment yield of the Poumako Stream (Rowe and Marden, 1998). Sediment yield did however, increase for a 3-month period in 1996 following the landslide, with much of the sediment mass forming a small dam across the stream. Then, during 1997 and 1998, sediment discharge relative to streamflow decreased as the slip-related sediment was flushed out of the catchment (Rowe and Marden, 1998; Rowe *et al.,* 2001). The undercutting of stream-banks and terraces (Coker *et al.,* 1990) and/or within-channel bed load and point bars have been identified as potentially significant sediment sources and could have accounted for the increased sediment yield; however, the absence of significant areas of stream bank activity or of substantial bed load deposits within the harvested reach of the Poumako Stream does not support these as being significant point sources of sediment. The conclusion drawn is that the measured rise in the Pokairoa Stream sediment yield, at a time when a significant part of the Pokairoa Catchment had been harvested, was derived from sources other than the harvested areas in the Poumako Stream.

It is further concluded that, given the practice of uphill-hauling away from stream channels (rather than across them), together with existing post-harvest management practices (replanting and oversowing) and under climatic conditions similar to that experienced during the period of investigation, it is unlikely future hauler-logging on similar pumiceous terrain will generate a significant increase in available sediment or its transportability to streams.

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