EROSION SOURCES AND SEDIMENT PATHWAYS TO STREAMS ASSOCIATED WITH FOREST HARVESTING ACTIVITIES IN NEW ZEALAND

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Abstract-- Forest harvesting and associated soil disturbances (e.g., earthworks) can increase catchment sediment yield, with potentially negative consequences for water quality and aquatic habitat. A major challenge for water quality protection is to anticipate where concentrated surface runoff and sediment will reach the stream (a.k.a., a 'breakthrough'). Improved understanding of sediment sources and pathways can guide forestry practices to control erosion and disrupt concentrated surface runoff. This study involved walking along intermittent and perennial stream channels associated with 23 recent plantation forest harvests throughout New Zealand to quantify the spatial frequency of breakthroughs and characterise their sources. For road-stream crossings that contributed sediment to the stream, the Universal Soil Loss Equation modified for forest land was used to estimate annual sediment delivery rates. Time since harvest completion was typically 2 to 12 months, while harvest area ranged from 4 to 67 hectares. Breakthrough frequency for timber harvests using ground-based skidding was 1.9 times that of cable-yarding extraction (6.2 versus 3.3 breakthroughs per stream kilometre). Overall, 73% of breakthroughs were associated with concentrated runoff from roads, skid trails, stream crossing approaches, and ruts from machine tracks on hillslopes directed toward streams. Estimates of sediment delivery at road-stream crossings, which accounted for 23% of all breakthroughs, were highest for skid trails (median = 70.8 tonnes/ha/year), followed by truck road ditches and running surfaces (3.9 and 1.6 tonnes/ha/year, respectively). These results emphasize the importance of implementing surface cover and adequately spacing water control structures on highly trafficked areas during harvesting activities and site closure. While surface runoff connections between roads and streams cannot be eliminated, the severity of accelerated erosion and their impacts can be minimised.

INTRODUCTION

Forest roads, skid trails, and stream crossings are widely recognized as the predominant sources of surface erosion and sediment delivery associated with forest harvesting operations (Sidle and others 2004, Wemple, Jones, and Grant 1996). Despite decades of refinements to forestry best management practices (BMPs) timber harvesting is still associated with short-term increases in catchment sediment yield (Fahey, Marden, and Phillips 2003). While eliminating sediment delivery through improved BMP technology or implementation may be impossible, opportunities still exist to lessen the severity of sediment inputs that can negatively impact water quality and aquatic habitat.

Many forestry BMP effectiveness studies have focused on reducing erosion (Anderson and Lockaby 2011, Brown, Aust, and McGuire 2013, Cristan and others 2016), but comparatively less is known about how (and how often) erosion sources become connected to stream channels. Recent studies have focused on understanding the spatial frequency and physical characteristics of sediment pathways to streams in order to guide site-specific BMP prescriptions for erosion control, sediment trapping, or reducing the volume and velocity of concentrated overland flow (Bowker, Stringer, Barton, and Fei 2010, Croke and Hairsine 2006). For example, Lang and others (2015) and Rivenbark and Jackson (2004) examined ephemeral concentrated flow paths entering streamside management zones (SMZs) (a.k.a., breakthroughs) associated with recent harvesting in the Piedmont physiographic region of the south-eastern U.S. On average, one breakthrough occurred for every 6 to 8 harvested hectares. However, breakthrough spatial frequency was highly variable from site to site and breakthroughs were non-uniformly distributed throughout forest operational areas. Both studies identified convergent areas (e.g., gullies and swales), surface runoff from roads and skid trails, and road-stream crossings as the most common breakthrough sources. Rivenbark and Jackson (2004) found that large contributing areas (mean = 0.4 ha), minimal litter cover, and/or steep slopes characterized the locations where breakthroughs occurred. They concluded that the sediment trapping efficiency of SMZs could be improved by maximizing ground cover, improving road runoff dispersal, increasing resistance to probable surface overland flow paths, and selectively increasing SMZ widths in problem areas.

Management of sediment pathways is particularly relevant for the New Zealand plantation forest industry, which currently harvests about 30 million m^3 of timber (predominantly *Pinus radiata)* annually (NZFOA 2014). Harvest volumes are predicted to increase to 42 million m^3/year by 2025 (NZFOA 2014). Much of the forestland is first-rotation plantation forest on terrain characterized as erodible hill country (Amishev and others 2014), which lacks the road infrastructure needed for harvesting. Annual estimates for new road construction range between 1,400 and 2,000 km per year for the next decade, the majority of which will be secondary and lower-standard access roads (Fairbrother 2012, Neilson 2012). Concurrent with the potential water quality risk associated with increased harvesting and earthworks, the requirement for water protection in planted forests (and elsewhere) is being raised by environmental regulatory initiatives such as the 2014 National Policy Statement for Freshwater Management (Ministry for the Environment 2014) and the impending National Environmental Standard for Plantation Forestry (NES-PF) (Ministry for Primary Industries 2015). The NES-PF will standardize forestry BMPs across the country, whereas BMPs are currently developed and implemented at a regional level. The timber harvest expansion in New Zealand represents an opportunity to better understand and manage sediment pathways to streams.

The objectives of this study are to: 1) Quantify the spatial frequency of breakthroughs associated with recent forest harvesting activities in New Zealand; 2) Identify specific sources of breakthroughs and their relative frequency; 3) Evaluate hydrologic connectivity and potential rates of sediment delivery at road-stream crossings; 4) Evaluate the characteristics of adjacent hillslopes that do and do not contribute sediment to the stream channel; and 5) Make recommendations, where applicable, about BMP improvements to reduce the likelihood of breakthroughs.

METHODS

Forestry companies were contacted to select harvest sites that met the following criteria: 1) At least one perennial or intermittent stream within the harvest area, as evidenced by a well-defined, scoured channel; 2) Recent harvest (3 to 12 months ago); 3) Harvest site to remain in plantation forestry; and 4) Harvest area < 20 ha. Perennial and intermittent stream channels associated with 23 recently harvested sites throughout New Zealand were surveyed for evidence of breakthroughs. Sites spanned the following regions: Bay of Plenty (2), Wairarapa (1), Tasman (3), Canterbury (10), Otago (5), and Southland (2). Time since harvest completion ranged from 2 to 12 months, except for three sites (also included in this study), which were harvested 2 years beforehand. Breakthrough surveys typically occurred between 2 and 12 months after harvest completion for two reasons: Firstly, a 2-month lag time should increase the likelihood that one or more runoff-producing events had occurred prior to the survey. Secondly, recently disturbed soil would be relatively susceptible to water erosion.

Surveys were completed by walking immediately adjacent to stream channels (or next to buffers of native vegetation, if applicable) and looking for evidence of concentrated overland flow (e.g., surface scour) and/or sediment delivery to the stream channel (Figure 1). This is in contrast to Rivenbark and Jackson (2004) and Lang et al. (2015), who walked SMZ perimeters searching for evidence of breakthroughs in the Georgia and Virginia Piedmont, where the minimum SMZ width for intermittent streams is 6 and 15.2 m, respectively, and SMZs are composed of hardwood forests. In New Zealand's large-scale commercial forests, the silvicultural prescription is typically clearcut harvesting of radiata pine, which can extend to the stream channel if a native forest buffer is not present. New Zealand's NES-PF will establish a minimum buffer ('setback') distance of 5 meters for perennial streams with a bankfull width of less than 3 m for the following forest management activities: afforestation, earthworks, harvesting, and mechanical land preparation (Ministry for Primary Industries 2015).

Figure 1. Example of a sediment breakthrough to an ephemeral stream channel. This breakthrough resulted from a landing failure. Photo credit: Kristopher Brown.

Breakthrough flowpaths were followed upslope to identify the erosion source and to describe the hydrologic contributing area associated with the breakthrough. Hillslopes and gullies not contributing to breakthroughs were also measured to compare the geomorphic characteristics of harvest areas that do and do not contribute runoff and sediment to streams. Excepting stream crossing approaches, logistic regression was used to predict the likelihood of a breakthrough given upslope contributing area, slope, bare soil percentage, aspect, topography (convergent, divergent, or planar slopes), and the hydrologic influence of roads, skid trails, or machine traffic disturbance (i.e., ruts from mechanized harvesting , slash windrowing, or overland skidder traffic). The presence or absence of roads or skid trails and machine traffic disturbance was evaluated for each data point and a disturbance ranking was created as follows (1 is lowest, 4 is highest): 1) No roads, skid trails, or machine traffic disturbance; 2) Machine traffic disturbance only; 3) Roads and trails only; 4) Both roads/trails and machine traffic disturbance present.

Stream crossing approaches were evaluated separately because these potential breakthrough sources are easily identified, defined (i.e., in terms of contributing hydrologic area), and managed. Runoff and erosion control is important at road-stream crossings because erosion sources can have a relatively direct and unimpeded flowpath to the stream. The Universal Soil Loss Equation modified for forestland (USLE-forest) (Dissmeyer and Foster 1984) was used to estimate annual erosion rates for road-stream crossing approaches that led to breakthroughs. Unlike Lang et al. (2015), not all stream-crossing approaches were considered to be breakthroughs. Where there was no evidence of surface scour or sediment delivery to the stream channel, as was often the case for overland skid trails with short approaches and slash barriers for water and erosion control, these approaches were considered to be non-breakthroughs. Potential erosion rates were estimated for truck road surfaces, ditches (if applicable), and skid trail surfaces. Field measurements related to the approaches included slope, bare soil percentage, surface roughness, and contributing hydrologic area (i.e. drainage length x width). Drainage length was defined as the distance from the stream to the nearest functioning water control structure (e.g., water bar, cut-out, or cross-drain culvert) or other topographical feature that re-directed surface runoff from the road and away from the stream channel. Rainfall erosivity index values (R-values) were selected from a map of R-values for New Zealand (Haas, 2014). For soil erodibility, an intermediate K-value of 0.033 (t ha hr / ha MJ mm) (Foster et al. 1981) was chosen for truck road surfaces because soils associated with the running surface are highly modified. For example, many forest road pavements in New Zealand are comprised of a compacted subgrade soil layer underlying an aggregate surface layer (Fairbrother, 2011).

RESULTS AND DISCUSSION

Breakthrough Spatial Frequency

Total harvest area per site ranged from 4 to 67 ha, with a median of 23 ha. Timber was extracted with ground-based machines (9 sites), cable yarders (9 sites), and a mix of both (5 sites). In total, 23 km of stream channel were traversed in association with 552 harvested hectares to count the number of breakthroughs. Overall, 106 breakthroughs were found and the median number of breakthroughs per kilometre of stream was 3.4, or 1 breakthrough for every 6.5 harvested hectares. Sites with ground-based extraction had 1.9 times more breakthroughs per kilometre of stream than cable yarding due to higher near-channel disturbances from skid trails. Breakthrough frequency per kilometre of stream ranged from 0 to 23.9 for ground-based extraction, 0 to 9.5 for cable yarding, and 0.5 to 5.3 for sites using both ground-based machines and cable yarders to extract timber (Table 1).

Two ground-based harvests accounted for 35% of all breakthroughs, suggesting that forest harvesting does not result in ubiquitous sediment inputs, but that one or more ‘problem’ sites could dominate downstream water quality impacts. At one of these sites, five breakthroughs resulted from surface runoff and fill slope slumps from a truck road and associated stream crossing constructed in highly erodible silty loam soils. An additional 10 breakthroughs resulted from naturally-occurring erosion features (i.e., many small land slips, rills and one gully) with no obvious connections to harvesting or road construction activities. At the other problem site, most of the breakthroughs were associated with deep rutting from skid trails and machine traffic near the stream with no provisioning of surface cover during site closure (Figure 2).

Table 1. Breakthrough spatial frequency per kilometre of stream channel and per harvested hectare. The data is organized by extraction method (ground-based, cable yarder, and both) and in order of decreasing breakthrough spatial frequency. For the overall summary, sum totals are represented with * and median values with **.

Region	Channel length (km)	Harvest area (ha)	Breakthroughs	Breakthroughs per km	Breakthroughs per hectare
Ground-based extraction					
Tasman	0.7	12	16	23.9	1.33
Canterbury	1.9	23	21	10.9	0.91
Southland	0.6	24	5	8.3	0.21
Canterbury	1.4	30	9	6.5	0.30
Tasman	0.7	8	4	6.2	0.51
Otago	1.1	24	6	5.5	0.25
Otago	0.9	17	3	3.3	0.18
Canterbury	0.7	25	2	3.1	0.08
Otago	0.9	12	0	0	0
Cable yarder extraction					
Tasman	0.6	8	6	9.5	0.71
Bay of Plenty	0.6	33	5	8.3	0.15
Canterbury	1.2	23	5	4.2	0.22
Canterbury	0.9	12	3	3.5	0.24
Canterbury	0.6	19	2	3.3	0.10
Canterbury	1.3	27	2	1.5	0.07
Canterbury	0.1	4	0	0	0
Canterbury	0.2	14	0	0	0
Otago	0.7	26	0	0	0
Both ground-based and cable yarder extraction					
Wairarapa	1.5	36	8	5.3	0.22
Canterbury	1.5	47	5	3.4	0.11
Bay of Plenty	1.4	13	2	1.4	0.15
Southland	1.8	47	1	0.6	0.02
Otago	1.9	67	1	0.5	0.01
Summary	**23***	**552***	**106***	**3.4****	**0.15****

Figure 2. Photo depicting a badly rutted skid trail post-harvest. Photo credit: Kristopher Brown.

Breakthrough Sources

Most breakthroughs (50%) were caused by concentrated runoff from roads, skid trails, or machine traffic disturbance on the hillslope (Figure 3). An additional 23% of breakthroughs occurred where roads and skid trails crossed streams. Thus, 73% of breakthroughs were associated with roads, trails, and machine tracks on the hillslope. These findings reinforce the importance of pre-harvest planning efforts to minimise earthworks, locate roads and stream crossings to avoid steep gradients, and maintain a buffer (e.g., an SMZ or slash barrier) between disturbed soil and streams. Such practices should reduce the occurrence of road-related sediment breakthroughs and reduce the severity of impacts to water quality. Furthermore, road-stream crossings represent easy targets that can be identified during the planning stage and BMPs can be prescribed for water and erosion control.

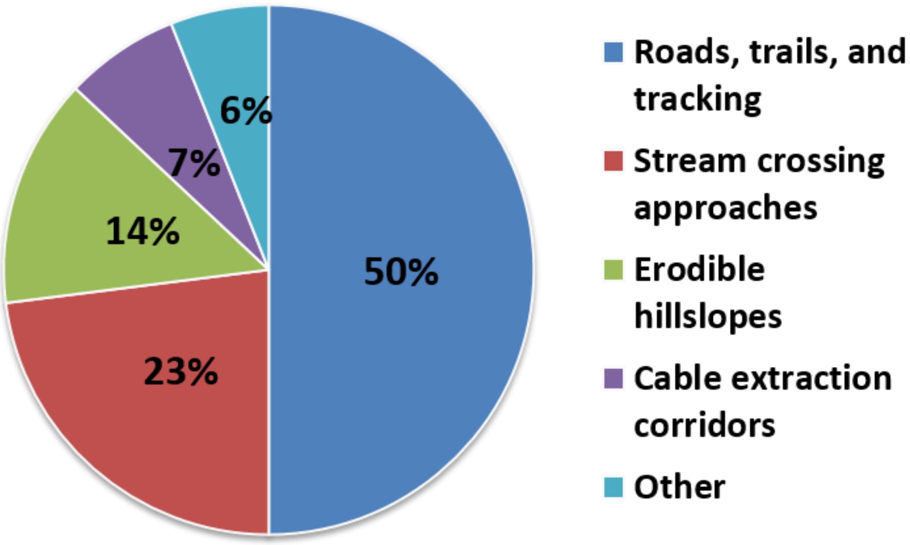

Figure 3. Breakthrough sources and their relative frequency. N = 53 for ‘Roads, trails, and tracking’, 24 for ‘Stream crossing approaches’, 15 for ‘Erodible hillslopes’, 7 for ‘Cable extraction corridors’, and 6 for ‘Other’.

Naturally occurring highly erodible hillslopes generated 14% of the overall breakthrough total. These breakthroughs were not necessarily associated with direct harvest disturbance, but instead with small land slips that may have resulted from the vegetation removal. Additional BMPs, such as dry-weather harvesting and slash dispersal on actively eroding areas, may be necessary to avoid exacerbating these erosion sources during harvesting. Seven percent of all breakthroughs were associated with cable yarding corridors that scoured hillslopes as they crossed stream channels. Six percent of all breakthroughs could not be readily classified into any of the aforementioned categories. They included one landing failure (Figure 1), runoff from a saturated bench below a landing, one landing/staging area built over the main stream channel, one uprooted tree near the stream, and two undisturbed gullies that were flowing with water during a storm event.

Connectivity at Road-Stream Crossings

Stream crossing approaches associated with log truck roads (lower-standard spur and secondary roads) delivered concentrated runoff to streams more often (17 of 21 approaches) than those of skid trails (10 of 35 approaches). However, skid trail stream crossings were more frequent. Surfaces of log truck roads are compact by design in order to support heavy loads and prevent water infiltration into the road subgrade. Thus, there is a greater potential for surface runoff generation, even for low-intensity rainfall events. Conversely, skid trail crossings that did not contribute to breakthroughs were typically not bladed (i.e., cut into the hillside), not as compact, and retained some of the protective functions of the forest floor.

The distance from the stream to the nearest water control structure was important for understanding road-to-stream hydrologic connectivity. Median drainage length for road-stream crossings that led to breakthroughs was 73 m, ranging from 5 to 185 m (Figure 4). Conversely, median drainage length for road-stream crossings that did not lead to breakthroughs was 12 m, ranging from 5 to 61 m. These findings suggest that while it may be difficult to eliminate connectivity from log truck roads at stream crossings (due to their inherently compact design), the severity of water quality impacts can be managed by adding water control structures to reduce the drainage length. Sessions (2007) recommended reducing the drainage length at road-stream crossings to approximately 20 m. Of the 21 truck road approaches to stream crossings measured in this study, only 4 had a drainage structure within 20 m of the stream. For skid trail crossings, connectivity could be reduced by using overland (not bladed) skid trails where slope steepness allows, as well as installing cut-outs for water control and using slash or mulch for surface cover during road closure.

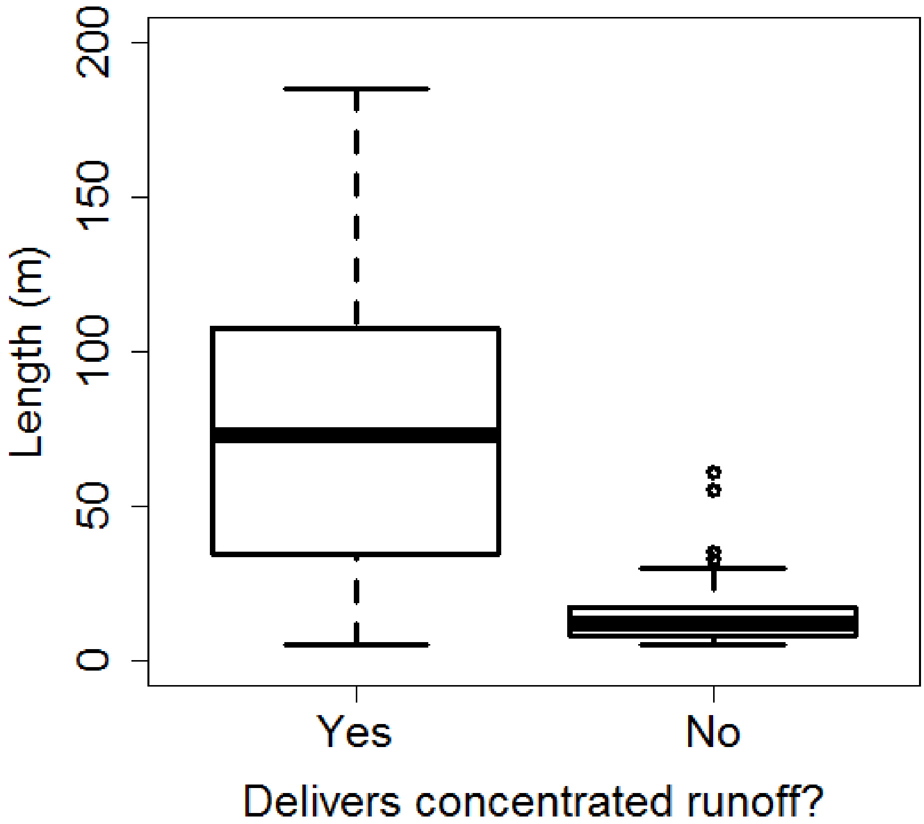

Figure 4. Box and whisker plots (showing the 5th, 25th, 50th, 75th, and 95th percentiles) of stream crossing approach length (m) in relation to whether or not the approach delivered concentrated surface runoff to the stream (n = 27 for 'Yes' and n = 29 for 'No'). Approach length was defined as the distance from the stream to the nearest road drainage structure (e.g. water bar, turnout, or culvert cross-drain) or topographic feature that moved surface runoff away from the road.

Potential Erosion Rates for Breakthroughs at Road-Stream Crossings

Erosion estimates ranged from 0.5 to 13.4 tonnes/ha/yr for truck road surfaces, 0.9 to 20.1 tonnes/ha/yr for truck road ditches, and 5.9 to 314.8 tonnes/ha/yr for skid trail surfaces (Table 2). The median potential erosion rate for skid trails was 44 times greater than truck road surfaces and 18 times greater than truck road ditches (Figure 5) because skid trails that led to breakthroughs were steep (median = 16.5% slope) with 0 to 30% surface cover. This finding highlights the importance of closing skid trails properly, especially at stream crossings. Several studies have demonstrated the sediment-reduction efficacy of skid trail closure techniques, such as water bar installation, plus slash or mulch application (Sawyers, Bolding, Aust, and Lakel 2012, Wade, Bolding, Aust, and Lakel 2012, Vinson 2016).

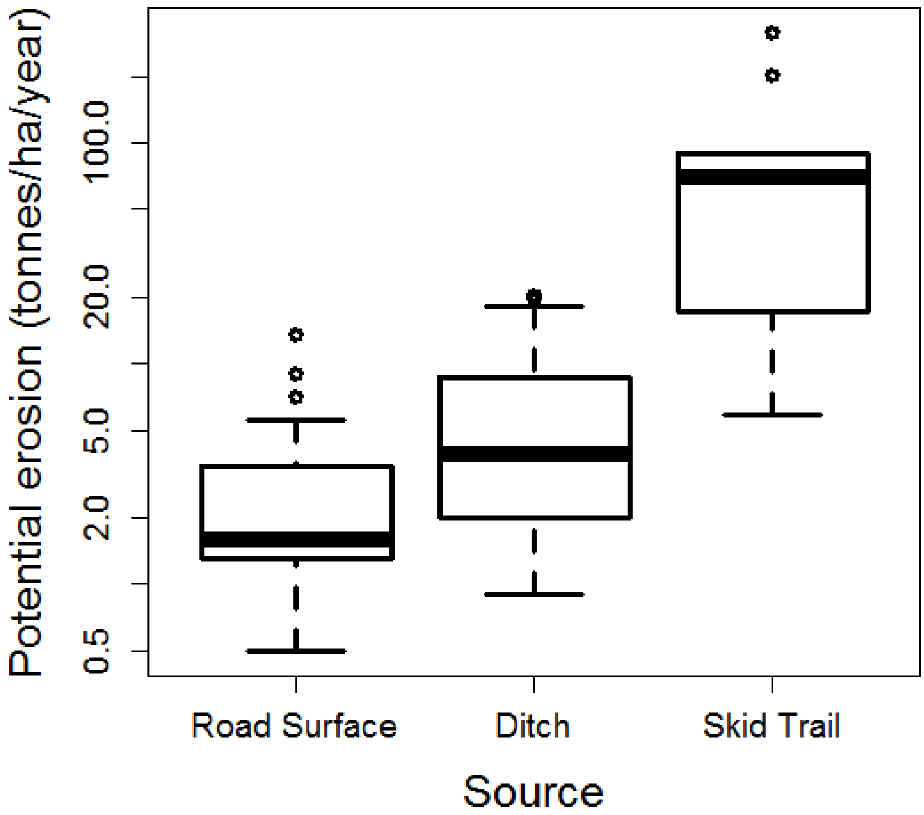

Figure 5. Box and whisker plots (showing the 5th, 25th, 50th, 75th, and 95th percentiles) of potential erosion rates of log truck and skid trail stream-crossing approaches (n = 17, 14, and 10, respectively, for truck road surfaces, truck road ditches, and skid trails). Each of these approaches contributed to a breakthrough.

Table 2. Summary of estimated erosion rates (t/ha/yr) for road-stream crossing approaches that led to breakthroughs. Estimated erosion rates are shown here for road and skid trail surfaces only.

Region	Drainage length (m)	Slope (%)	Bare soil (%)	Potential erosion (t/ha/yr)
Log truck roads				
Tasman	175	10	30	13.4
Wairarapa	91	12	35	9.0
Otago	185	12	62	7.1
Canterbury	110	9	50	5.5
Southland	105	11	20	3.4
Canterbury	15	9	50	2.9
Otago	79	7	40	2.0
Tasman	51	2	40	1.9
Otago	147	7	27	1.6
Wairarapa	31	3	50	1.6
Wairarapa	49	5	25	1.6
Canterbury	100	5	30	1.3
Canterbury	144	14	20	1.3

Otago	155	7	15	1.2
Southland	50	4	20	0.8
Canterbury	15	2	50	0.6
Otago	180	3	35	0.5
Skid trails				
Tasman	25	52	80	314.8
Tasman	43	33	80	203.7
Tasman	76	17	85	89.8
Tasman	23	16	100	76.6
Tasman	95	12	100	76.6
Bay of Plenty	6	33	70	65.0
Bay of Plenty	5	19	70	23.7
Otago	73	16	80	17.3
Canterbury	51	14	90	15.3
Canterbury	38	10	80	5.9

Truck road surfaces with potential erosion rates less than 2 tonnes/ha/yr had a median bare soil percentage, slope, and drainage length of 29%, 4%, and 76 m, respectively. Thus, while drainage lengths were relatively long, gentle slopes and/or good surface cover reduced potential erosion rates. Pavement design for lower-standard spur roads in New Zealand typically employs a single 'improved' layer, consisting of compacted basecourse aggregate overlying a compacted subgrade soil. This aggregate layer provided good surface cover. Potential erosion rates were higher in truck road ditches, mainly because ditches were typically unsurfaced.

Characteristics of Upslope Contributing Areas that Led to Breakthroughs

Excluding stream crossing approaches, breakthrough likelihood of occurrence increased with increasing bare soil percentage ($Z=5.2$, $p<0.001$) (Figure 6). Hillslopes with no roads, skid trails, or machine traffic disturbance ($Z=-2.4$, $p=0.02$) or only machine traffic disturbance ($Z=-2.8$, $p=0.004$) decreased the likelihood of a breakthrough. Median bare soil percentage for upslope areas contributing to breakthroughs (40%) was 4 times higher than that of those that did not (10% bare soil).

Breakthrough relative frequency was examined in relation to the severity of disturbance from roads, skid trails, and machine traffic on hillslopes adjacent to the stream (344 total cases). In 186 cases where no roads, skid trails, or machine tracks were present, only 25 breakthroughs were found. In 50 cases where machine tracks were present, but not roads or skid trails, 10 breakthroughs were found. In 59 cases where roads and skid trails were present but not machine tracks, 18 breakthroughs were found. In 49 cases where roads, skid trails, and machine tracks were present, 24 breakthroughs were found. Thus, when more highly compacted or disturbed areas were present upslope, breakthroughs occurred more frequently.

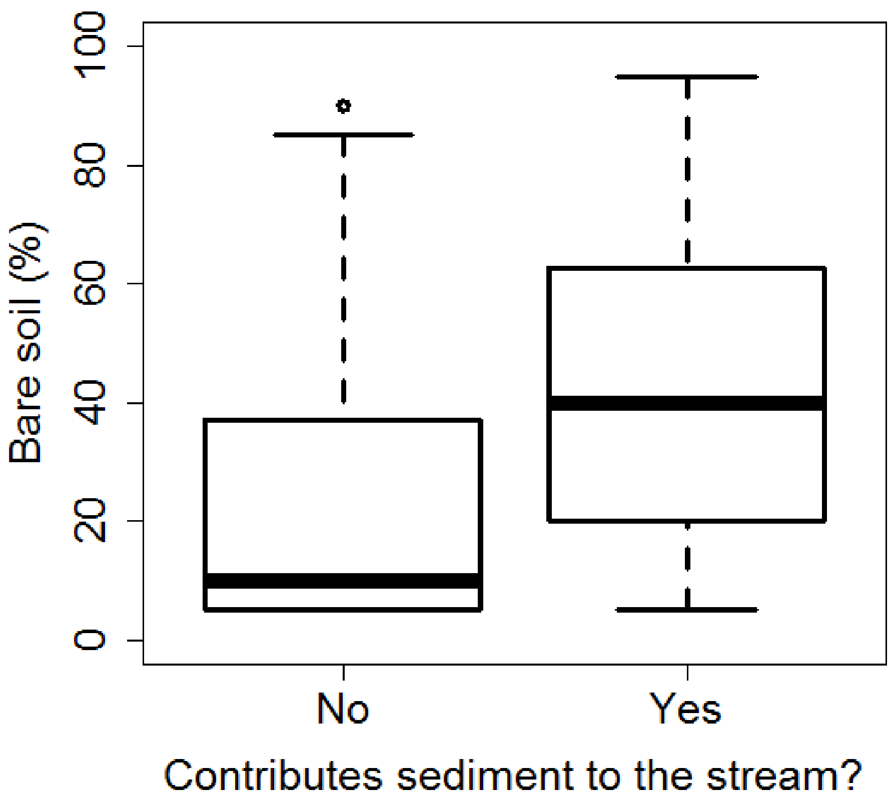

Figure 6. Box and whisker plots (showing the 5th, 25th, 50th, 75th, and 95th percentiles) of bare soil percentage for upslope contributing areas that did (n = 77) and did not (n = 267) lead to a breakthrough.

CONCLUSIONS

Negative impacts to water quality can occur when sediment from forest harvesting operations breaks through to stream channels. This study examined intermittent and perennial stream channels associated with 23 recent plantation forest harvests throughout New Zealand to quantify the spatial frequency of breakthroughs, characterise their sources, and contribute to the improved understanding and management of sediment pathways to streams. Overall, the median number of breakthroughs per kilometre of stream channel was 3.4. Ground-based extraction was typically associated with more soil disturbance from skid trails, thus the median breakthrough spatial frequency was 1.9 times that of cable yarding (i.e., 6.2 vs 3.3 breakthroughs per km of stream). The majority of breakthroughs (73%) were associated with truck roads, skid trails, or machine traffic disturbance on hillslopes, which emphasizes the importance of minimizing earthworks, locating roads and stream crossings to avoid steep gradients, maintaining a buffer between disturbed soil and streams, and prescribing BMPs for surface cover and water control.

This study identified two areas for improved BMPs to either reduce road-to-stream connectivity or lessen the severity of water quality impacts from breakthroughs (i.e., implement effective BMPs). The first is to locate road-stream crossings to avoid steep approaches and, if applicable, use water control structures (i.e., cross-drain culverts and cut-outs) to reduce surface runoff volumes that discharge directly to the stream channel. The second is to ensure that temporary stream crossings are closed properly, as potential erosion rates in this study exceeded 80 tonnes/ha/yr for steep skid trails with poor water control and surface cover. Closure techniques for skid trails are well-documented and include water bars and cut-outs, plus some type of surface cover (e.g., slash or mulch application). Both skid trails and temporary log truck roads should be periodically inspected post-harvest to ensure that water control structures are functioning properly.

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