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FOREST ROAD EROSION IN THE GRANITE TERRAIN OF SOUTHWEST NELSON, NEW ZEALAND

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ABSTRACT

Past and present sediment production rates from surface erosion on roads in erodible granite terrain of two adjacent forests in southwest Nelson are presented. Yields were monitored for 20 to 32 months at five plots on representative sections of forest roads. Data were collected between 1980 and 1983 from 18 plots on sidecast. Erosivity indices were closely related to sediment production during individual storms. Average annual yields ranged from 1.6 kg m^{-2} to 11 kg m^{-2} for the road surface-drainage ditch combination and from 1 kg m^{-2} to 5 kg m^{-2} for sidecast. These figures are extrapolated, with the aid of a detailed road survey, to the 209-km road network on the 12,500 ha of granite terrain in both forests to estimate total sediment supply from surface erosion. Current yields are estimated at 4700 t yr^{-1} (37 t km^{-2} of forest), and at the time of peak road construction, 11,000 t yr^{-1} (88 t km^{-2}). After upgrading and expansion of the road network at harvesting, sediment yields are predicted to rise to somewhere between 20,000 t yr^{-1} and 40,000 t yr^{-1} (160 t km^{-2} to 320 t km^{-2}). Background erosion rates for nearby river catchments are estimated at about 500 t km^{-2} yr^{-1}.

INTRODUCTION

Many forests planted on steepland areas in New Zealand are rapidly approaching maturity, and an expanded or upgraded network of forest roads will be needed for harvesting. Studies on steeplands in North America have clearly shown that the construction of logging and access roads can accelerate surface erosion and mass movement, leading to channel aggradation and impaired water quality (e.g., Fredriksen (1970) in western Oregon; Megahan and Kidd (1972), and Megahan *et al.* (1986) in central Idaho; Reid *et al.* (1981) and Reid and Dunne (1984) in Washington State; Rice *et al.* (1979) in California; and Swift (1984) in North Carolina).

Little research has been done on road-related erosion and sedimentation in New Zealand. Mosley (1980) used volumetric measurements of erosional features to determine how much material was entering stream channels from road sources in the Dart River area of southwest Nelson. Sediment yield in a small (8.3 ha) skidder-logged Westland catchment with a mid-slope access road was eight times higher than that in an adjacent undisturbed catchment (O'Loughlin *et al.*, 1980). Neither of these studies measured erosion rates from actual road surfaces or from cutbanks and sidecast.

The primary objectives of this study are to estimate past and current rates of sediment supply from the existing road network in an area known to be highly erodible, and to assess the impact that additional road building and upgrading are likely to have on sediment yields to local stream courses. The study also seeks to characterise the relationship between selected parameters of storm magnitude and amounts of sediment produced, and to identify the proportion of sediment released from each of the three main components (cutbank, road surface, and sidecast).

The granite terrain of Golden Downs and Motueka Forests was chosen for study because it has already been identified as an area of high erosion potential (Mosley, 1980). Visual evidence also suggests that large amounts of loose granite disturbed during road construction have already entered nearby stream channels. Fears have been expressed by local residents, regional authorities, and recreationists about the effect of increased sedimentation on downstream water values. Sediment yield monitored on these erosion-prone granites would therefore serve as a useful bench mark for erodible steepland forested areas elsewhere in New Zealand. Moreover, the weathered granite of southwest Nelson has textural similarities to the pumice underlying commercial forests in the central North Island, and the results should indicate how soils with low cohesion can be expected to respond to roading operations.

FIELD AREA

Location

Golden Downs and Motueka Forests are located in the northwestern part of the South Island, 40 km southwest and west of Nelson, respectively (Fig. 1). Golden Downs Forest covers an area of approximately 49,000 ha, of which 31,950 ha are stocked, mostly with *Pinus radiata* (Ministry of Forestry, 1988). The smaller Motueka Forest covers 7785 ha, with a stocked plantation area of 3665 ha, the balance being in indigenous forest.

Geology and Soils

The rock type underlying most of Golden Downs Forest is the Moutere Gravel formation of Plio-Pleistocene age. The indurated nature of this material minimises surface erosion and mass movement, even during harvesting and roading operations. By contrast, much of the western portion of Golden Downs Forest and virtually all of Motueka Forest are located on the late Cretaceous Separation Point Batholith, described as a porphyritic, equigranular, biotite granite-to-granodiorite (Johnston, 1983). This granite terrain has been severely dissected, and in general has steeper slopes and greater local relief than the Moutere Gravels. Over much of the granite a deeply-weathered, almost saprolitic mantle of loose, crumbly, sand-sized material has developed. Evidence of accelerated surface erosion is widespread in areas underlain by the granite, but is particularly noticeable in the vicinity of access roads where sediment mobilised by road construction can often be seen extending down gullied slopes into main water courses.

Soils formed on the weathered granite are a steepland variant of the zonal yellow-brown earths. They are shallow, with greyish-brown sandy loam A horizons overlying loamy yellowish-brown subsoils (Chittenden *et al.*, 1966). The upland varieties have developed in sandy regolith on relatively competent granite. At lower altitudes Kaiteriteri hill soils, formed on accumulated weathering products, are normally more erosion-prone than their upland counterparts.

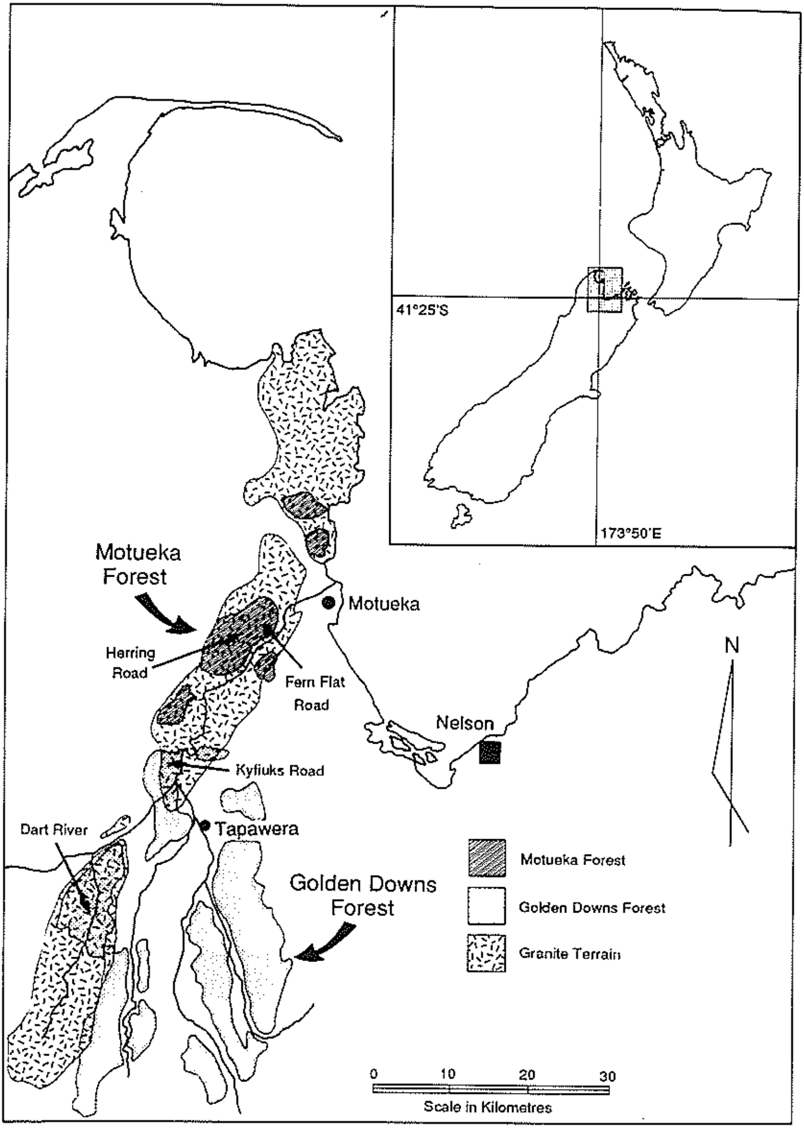

FIG. 1—Location map showing Golden Downs and Motueka Forests, the extent of granite, and location of field sites.

Climate

The humid temperate climate of southwest Nelson is dominated by a succession of eastward-moving anticyclones and troughs of low pressure which are normally preceded by cold fronts. High intensity rain storms can occur at any time of the year and may be highly localised. Droughts are also common, especially in summer.

The nearest climatological station to the field area is at Golden Downs Forest headquarters near Tapawera (Fig. 1) at 274 m a.s.l. The mean annual air temperature at this site is 10.5°C, the January mean is 15.7°C, and the July mean 4.6°C (New Zealand Meteorological Service, 1983). The mean annual number of ground and screen frosts is 118 and 74, respectively. Mean annual rainfall (1307 mm) is fairly evenly distributed through the year, from a low of 89 mm in March to a high of 121 mm in April.

Characteristics of the Road Network

The major dimensions, gradients, and percent vegetation cover for all three road components (the cutbank and drainage ditch, the road surface, and the sidecast fill), plus aspect and consistency of the cutbank surface (loose or firm) were noted at 0.5-km intervals over the entire 209-km road network on granite in the two forests (Table 1).

The pattern and timing of past road construction corresponds to the planting schedule in the two forests. Most of the planting in compartments in Golden Downs Forest on granite was spread over an 11-year period from 1971 to 1981, and reached a peak in 1977 and 1978. Planting in Motueka Forest extends back to 1940, but most compartments were stocked from the mid 1960s to early 80s. Major roading began in 1970, with the bulk of the network constructed later in the decade.

DESCRIPTION OF FIELD SITES

In December 1985 three plots were established on Kyfiuks Road in compartment 443 of Golden Downs Forest, 10 km north-west of Tapawera (Fig. 1). The road surface, drainage ditch, and cutbank were graded to represent conditions soon after construction. Monitoring began in January 1986. In early 1987 two additional plots were installed on Herring Road in Motueka Forest (compartment 57), 9 km south-west of Motueka. The section of road chosen had higher cutbanks and slightly steeper gradients than Kyfiuks Road. At the same time a fourth plot was set up 1 km south of the initial three plots on Kyfiuks Road, in an area of reworked granite sand noted for high rates of sediment supply from loose cutbank material. Neither this plot nor those on Herring Road were graded before measurements began. The heights, widths, and gradients of the plots closely approximated the average values listed for Golden Downs and Motueka Forests (Table 1).

The section of Kyfiuks Road containing Plots 1, 2, and 3 was closed to traffic once measurements began. The remaining plot on Kyfiuks Road and Plots 1 and 2 on Herring Road were open to traffic, but there would have been no more than one or two light vehicle passes a week during the study.

Sections of road 25 m long by 4 m wide at each site (except Plot 1 on Herring Road which was 30 m long) were isolated by a system of flow barriers and ditches to form the runoff plots. At Plot 1 on Kyfiuks Road the cutbank was separated as a sediment source by ten 2.5-m long troughs positioned just above the drainage ditch (Fig. 2). These were designed to catch sediment from the

TABLE 1—Average dimensions and other road parameters for (a) the road network constructed on granite in Golden Downs and Motueka Forests, and for (b) Plots 1 to 4 Kyfiuks Road, and Plots 1 and 2 on Herring Road.

	(a) Forest Averages and Totals		(b) Kyfiuks Road				Herring Road	
	Golden Downs Forest	Motueka Forest	Plot 1	2	3	4	1	2
Road length (km)	95	114	*	*	*	*	*	*
Cutbank height (m)	4.8	4.1	3.3	4.6	5.1	6.6	8.5	7.0
Cutbank slope (°)	55	58	64	65	59	57	60	65
Avg. road width (m)	4.6	4.5	4.5	4.5	4.5	4.5	4.5	5.4
Avg. road gradient (°)	4.0	4.4	4.0	3.5	3.5	5.5	7.5	4.5
Gravel cover (%)	15	16	*	*	*	*	*	*
Sediment depth in drainage ditch (cm)	5	3	*	*	*	*	*	*
Sidecast slope (°)	29	29	*	*	*	*	*	*
Vegetation cover on sidecast (%)	75	70	*	*	*	*	*	*
Aspect	*	*	SSW	SSW	SSW	ESE	E	E

cutbank without restricting the flow of water down the drainage ditch. Thus, apart from Plot 1 on Kyfiuks Road, the catchment area for each plot included the cutbank, drainage ditch, and road surface. River-run gravel from local road metal supplies was spread across the surface of Plots 1 and 2 to approximate normal road surfacing procedures. Plot 3 was left freshly graded.

METHODS

Runoff and sediment production were measured at the first three plots on Kyfiuks Road, but sediment production only was measured at Plot 4. Rainfall was measured at the Kyfiuks Road trial with a Lambrecht automatic raingauge located adjacent to Plot 3. These data were used to estimate the kinetic energy and erosivity of individual storms. Erosivity during a storm depends largely on the energy of the incident rainfall. In this study the kinetic energy of a given storm was calculated from a procedure described by Morgan (1979), and the potential for a given rainfall event to cause erosion was estimated from Wischmeier and Smith's (1958) erosivity index, EI_{30}, which is the product of the storm's total kinetic energy ($J\ m^{-2}$) and the maximum 30-min rainfall intensity ($mm\ h^{-1}$).

Runoff and sediment production at Kyfiuks Road were measured with the aid of two 44-gallon drums positioned approximately 10 m downslope from each plot and connected to the plot by sections of PVC pipe (Fig. 2). Any sediment mobilised by runoff on the road surface and drainage ditch was channelled via a concrete apron into the pipe system, and transferred to the first drum where material coarser than silt settled out (Fig. 2). The second drum served as a stilling well-weir combination as a sheetmetal container was slung on its front with an 11° V-notch cut into its downslope face. Flow was computed by monitoring the water level in the drum with a Belfort recorder and converting this to millimetres of runoff. Peak discharges were also computed. During each visit, the water in the drum containing the impounded sediment was transferred to a spare drum, and the sediment was shovelled into buckets for weighing on-site. Representative samples were bagged and returned to the laboratory for drying, weighing, and particle-size analysis. The water was then transferred back to the sediment drum, the plumbing system flushed clean, and the whole system topped up with fresh water if required. The amount of water in the sediment removed from the drum was estimated from the sub-sample returned to the laboratory for drying. The total sediment yield was then expressed as the dry weight per unit area of contributing surface.

Sites were routinely visited once a month, but when possible were also visited after major storms. When sediment was found in the PVC pipes after large storms, the individual pipe sections were disconnected and the sediment was transferred to the buckets for weighing and inclusion in the total. Any excess sediment found in the concrete apron above the pipe inlets was also added to the total. There was no evidence to suggest that pipe blockages restricted the flow of water and sediment through the plumbing system.

The amount of sediment in the silt and clay range mobilised by storms but not trapped in the drum was estimated by collecting runoff samples at the pipe outlet for Plot 2 on Kyfiuks Road and calculating the suspended sediment concentrations in the laboratory.

Runoff was not measured at the two Herring Road plots, only sediment.

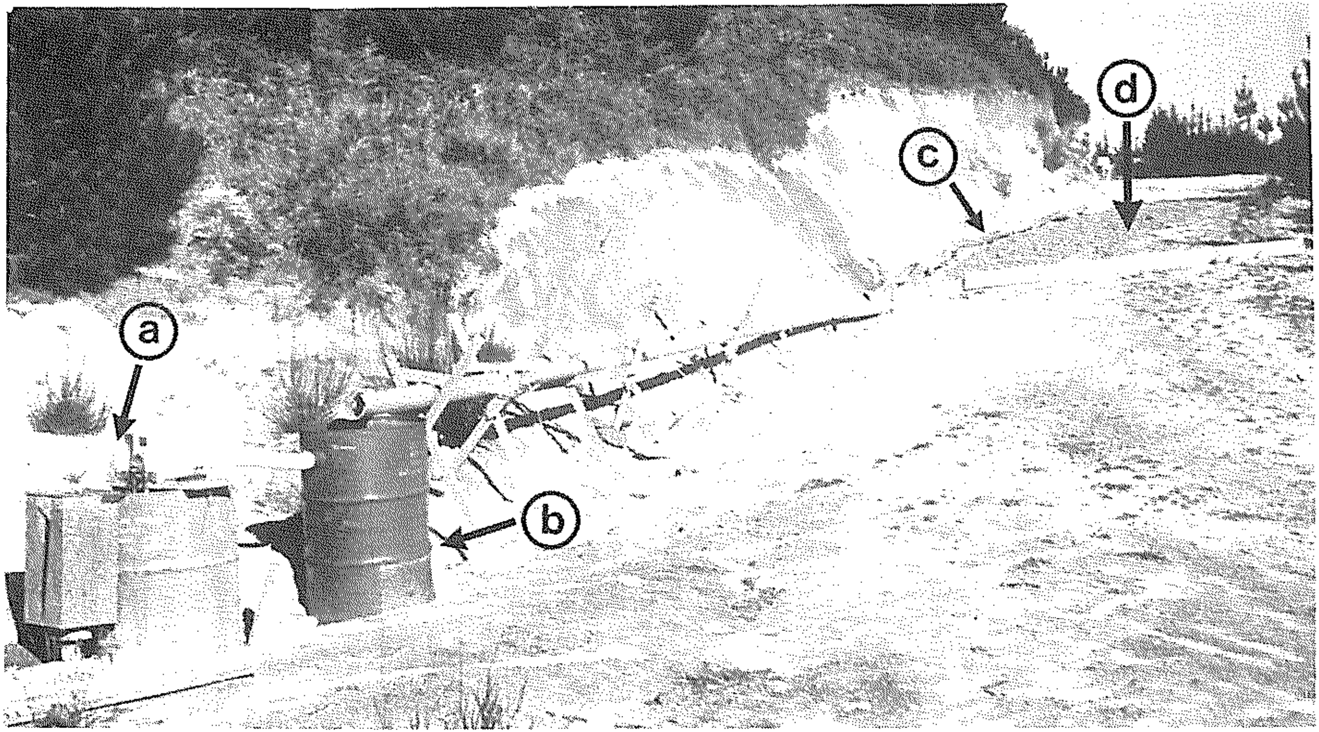

FIG. 2—View of Plot 1 on Kyfiuks Road showing (from left to right) (a) metal V-notch weir and water level recorder (on lower drum) for measuring runoff, (b) the upper drum for collecting sediment, the plumbing system for diverting water and sediment into the drum, (c) the troughs for trapping material dislodged from the cutbank, and (d) the road surface with gravel layer.

However, a Lambrecht raingauge located at Plot 1 enabled rainfall intensities to be calculated for the period March 1987 to August 1988.

A data-logging system was installed at Kyfiuks Road in January 1987. It provided a more detailed and time-synchronous record of peak discharges and maximum rainfall intensities than had been possible with the Belfort recorders and the Lambrecht raingauge.

RESULTS

Rainfall and Storm Characteristics

Weather conditions and storm activity during the study period were reasonably representative of average conditions for the area when compared with the long-term climatic record. Yearly rainfall totals for Golden Downs in 1986 and 1987 were below average (1261 mm and 1062 mm, respectively), but in the first 6 months of 1988 they were above average. Annual totals at Kyfiuks Road (10 km distant) for 1986 and 1987 were 1356 mm and 1314 mm, respectively.

The maximum 10-min rainfall intensity recorded at Kyfiuks Road by the data-logger was 6.8 mm on 9 November 1987, well below the estimated 5-yr return period intensity of 12 mm for this area (Tomlinson, 1980). The maximum 1-h intensity of 22.8 mm at Kyfiuks Road was recorded on the same day, and at Herring Road the maximum 1-h intensity of 18 mm was recorded on 15 February 1988. Both hourly figures were below the estimated 5-yr return intensities. However, the maximum 24-h total of 206 mm at Herring Road on 10 March 1988 was substantially higher than the estimated 5-yr return intensity.

A storm is defined here as a discrete rainfall event of 5 mm or more which is separated from preceding events by at least 6 h (Wischmeier and Smith, 1958). At the Kyfiuks Road plots, 133 storms were recorded during the 32 months of observation. Because Plot 2 is regarded as being more representative of the road network as a whole compared with Plots 1 and 3, emphasis is placed on the results from it.

Of the 133 storms, only 46 produced measurable surface runoff at Plot 2. Maximum storm yield was 127.4 mm on 15 February 1988, an amount that actually exceeded the measured rainfall for the same storm (81.4 mm). Similar excesses observed on five other occasions are thought to be explained by surface and subsurface runoff entering the plot from either above or through the cutbank. The maximum peak discharge of 4.8 *L* s^{-1} at Plot 2 was recorded on 9 November 1987, corresponding with the time of the maximum 1-h and 10-min intensities. The length of the rainfall record at the Herring Road site (April 1987 to August 1988) was substantially shorter than that for Kyfiuks Road, and therefore the number of storms exceeding 5 mm during this period was only 71.

The average available storm kinetic energy at Kyfiuks Road was 377 J m^{-2}, and the maximum 1933 J m^{-2}, (3 October 1988). The average for the erosivity index was 2790 J m^{-2}.mm h^{-1}, and the maximum was 27,181 J m^{-2}.mm h^{-1} (recorded on 9 November 1987). Over the shorter period of observation at Herring Road (March 1987 to August 1988), average and maximum values were both higher. Maximum kinetic energy and the erosivity index values were 4194 J m^{-2} and 57,886 J m^{-2}.mm h^{-1} respectively (recorded on 10 March 1988). These figures emphasise the highly localised nature of rainfall events in the southwest Nelson area.

Sediment Production and Storm Erosivity

It was obvious from the rainfall record that often more than one storm had contributed to the monthly sediment totals. There were 11 occasions at Plot 2 on Kyfiuks Road when the monthly sediment totals could be safely attributed to a single storm. At Plots 3 and 4 on Kyfiuks Road, and Plots 1 and 2 on Herring Road the number of occasions when the same criterion applied was 5, 13, 11, and 6, respectively. The variance in sediment totals explained by the corresponding storm erosivity indices (EI_{30}) using linear regression ranged from 95% for Plot 1 on Herring Road to 50% for Plot 2 on Kyfiuks Road.

Thresholds for Sediment Mobility

Apart from Plot 4 on Kyfiuks Road, at least 70% of the material collecting in the sediment drums was in the sand-size range (2 to 0.063 mm), with usually more than 15% in size classes finer than 0.063 mm. For Plot 2 on Kyfiuks Road the smallest storm capable of mobilising measurable quantities of sediment (>1 kg) occurred on 30 and 31 May 1986 (maximum intensity 6.0 mm h^{-1}, EI_{30} 2400 J m^{-2}.mm h^{-1}, runoff 1.7 mm, and peak discharge 0.05 $L\,s^{-1}$). Although storms in this range of maximum intensities and erosivities caused runoff and sediment movement at Plot 2 early in the study, they did not do so in the final 12 months. suggesting that the erosional resistance of the road surface increased with time since disturbance by grading, at least for storms of low magnitude. However, two major storms of similar size occurring almost a year apart produced virtually identical quantities of sediment, suggesting that any increase in surface resistance to erosion is not reflected in the impact of high-magnitude events.

For Plot 3, the smallest storm causing measurable sediment mobility (11 September 1987) was considerably larger than the equivalent storm at Plot 2. The maximum intensity was 13.3 mm h^{-1}, the EI_{30} 7800 J m^{-2}.mm h^{-1}, the storm runoff 3.6 mm, and the peak discharge 1.8 L s^{-1}. The absence of gravel and the depth of the accumulated sediment in the drainage ditch meant that rainfall, instead of being channelled into the collecting drum as surface runoff, had first to exceed the infiltration capacity of the porous sand on the road surface and in the drainage ditch. The surface runoff record for Plot 3 supports this interpretation; only 25 sediment-producing events were observed over the period compared with 40 and 46 at Plots 1 and 2, respectively.

As expected, the slightly steeper gradient, loose surface material, and the higher proportion of fine sand on the reworked granite at Plot 4 on Kyfiuks Road encouraged sediment mobility at lower rainfall intensities (down to 5.5 mm h^{-1}) and energy levels (EI_{30} of 1500 J m^{-2}.mm h^{-1}) than for the other sites.

Storm data for Herring Road revealed that for sediment to be mobilised at this site, rainfall intensity and the EI_{30} had to exceed 7 mm h^{-1} and 3500 J m^{-2}.mm h^{-1}, respectively.

Sediment Contributions from Individual Road Components

(a) Road surface: Yearly sediment totals from the gravelled surface of Plot 1 were almost an order of magnitude lower than the contribution from the cutbank (Table 2), and declined rapidly during the study. It was not possible to compare annual sediment amounts removed from the surface of Plot 1 with that from the other plots on Kyfiuks Road. Some of the material in the totals

TABLE 2—Yearly sediment totals (kg) at all plots

	Kyfiuks Road[1]						Herring Road	
		Plot 1		Plot 2	Plot 3	Plot 4	Plot 1	Plot 2
Year	Contribution from cutbank	Removed from surface	Retained in storage		Removed from surface & drainage ditch		Removed from surface & drainage ditch	
1986	1250	170	1080	345	254	*	*	*
1987	571	81	1570	497	256	1784	263	*
1988[2]	433	28	1975	280	183	1078	395	96

[1] Plots 1, 2, and 3 were graded in December 1985

[2] January to August

would have been derived from the drainage ditch, which in turn would have come from the cutbank.

(b) Cutbank: Monthly sediment accumulation in the troughs at the base of the cutbank (Fig. 3) showed a distinct winter maximum, attributable to diurnal needle-ice activity on the friable cutbank surface. Needle ice was observed on a number of occasions during winter site visits. The maximum recorded in the winter of 1986 may reflect the greater number of freeze-thaw days recorded at Golden Downs that year than in subsequent years. Alternatively, the cutbank surface may become more resistant with time as the more friable material is dislodged.

Estimates of sediment from the cutbank based on the volume of material that collected in the drainage ditch after grading at Plot 3 on Kyfiuks Road gave totals for 1986 (1500 kg) and 1987 (900 kg). These are similar to those measured in the troughs at Plot 1 (Table 2). Much of the material may remain in storage for some time. However, the road survey revealed little if any sediment actively collecting in drainage ditches elsewhere in the two forests (Table 1). Many cutbanks now have an indurated surface, suggesting that sediment accumulation and retention in drainage ditches is more of a problem immediately following disturbance. As a protective crust forms, the supply of sediment will dwindle, and that previously stored will continue to be removed until the drainage ditch is cleared of excess debris by runoff.

(c) Sidecast fill: An earlier Forest Research Institute investigation at Fern Flat Road in the Rocky River area, 5 km northeast of Herring Road in Motueka Forest (Fig. 1) monitored sediment production from several sources, including sidecast fill, on newly constructed road sections in the forest. This study compared the effectiveness of various vegetation types (trees, shrubs, and grasses) in reducing sediment yield, in much the same way that Megahan (1978) had done for granite road fill in the Deadwood area of the Idaho Batholith in northwestern United

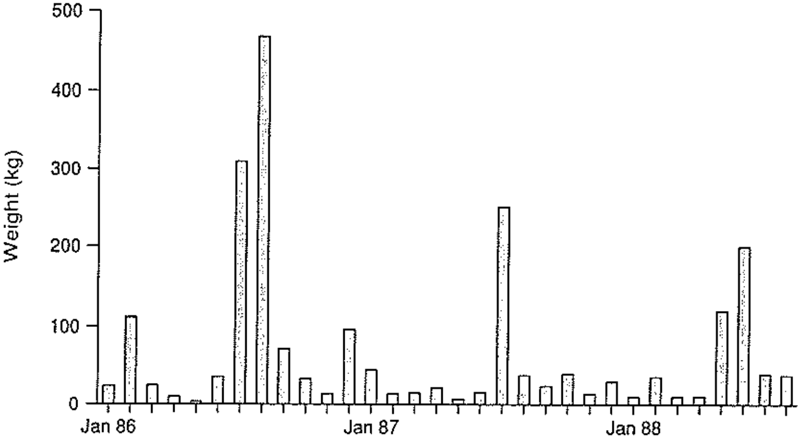

FIG. 3—Monthly sediment totals measured in the troughs located at the base of the cutbank at Plot 1, Kyfiuks Road for the period January 1986 to August 1988.

States. In January 1981, 18 erosion plots (20 m^2 each) were established in three groups on sidecast below sections of Fern Flat Road. Four of the six plots in each group were planted in a variety of grasses; one was planted in Douglas fir, and the other was left as a control. Six plots were destroyed in a storm in December 1981, but were replaced in May the following year with identical treatments. All measurements ceased in December 1983.

The mean annual sediment total for the 12 plots that survived through the 33 month observation period was 51 kg per plot. No clear relationship was observed between vegetation cover type and sediment production. However, the general decline in sediment yield with time (Table 3) suggests that the expansion of a vegetation cover across the sidecast surface coupled with surface hardening may bring about a reduction in sediment supply. The road survey showed that vegetation now extends over 73% of the sidecast surface. Thus, it is unlikely that this component of the road system is acting as a major source of sediment, except where its steepness and depth increases the likelihood of debris slides, or in areas where material has moved directly into local gullies. Gullies serve as temporary storage areas that can be flushed out periodically into major streams during infrequent high-intensity rainfall.

Annual Sediment Yield

Kyfiuks Road plots: At Plot 1 the freshly graded cutbank contributed 15.2 kg m^{-2} to the drainage ditch in 1986 and 7.0 kg m^{-2} the following year (Table 4). The annual sediment yield from the road surface alone averaged 0.9 kg m^{-2}, with a maximum of 1.7 kg m^{-2} in the first year after grading. The average annual yield for Plot 2, which includes the road surface and drainage ditch, averaged 3 kg m^{-2} per year. That for Plot 3 was just under 2 kg m^{-2}. Compared with the yield for Plot 1, these figures suggest that when the drainage ditch serves as a storage zone for material from the cutbank, it contributes up to three times the amount coming from the road surface. Annual sediment yields for the first few years after construction are therefore estimated to be between 3 and 4 kg m^{-2} of contributing surface (road and drainage ditch). Roads with steeper gradients would be expected to produce more material. Although the measured rates of 14.2 and 8.5 kg m^{-2} for 1987 and 1988 (January to August), respectively, at Plot 4 (gradient 5.5°) are higher, this site is located in an area of reworked granite regolith, and is thus more prone to surface erosion.

(b) Herring Road plots: Plots 1 and 2 on Herring Road had an annual yield of 2 kg m^{-2} (Table 4). However, unlike the Kyfiuks Road trial, neither of the Herring Road plots were graded before measurements commenced; furthermore, parts of the cutbank at both Herring Road plots appeared more stable than their graded counterparts at Kyfiuks Road, and are probably not contributing to the same degree. Thus, the yield figures quoted for Herring Road are believed to be more indicative of current yields from road surfaces in the two forests.

(c) Fern Flat Road plots: The average annual sediment yield from the plots located on sidecast at Fern Flat Road was 2 kg m^{-2}, rising to a maximum average of 5 kg m^{-2} for Plot 11 planted in Douglas fir. The maximum for any year was 11.3 kg m^{-2} in 1981 on Plot 11 (Table 3).

TABLE 3—Yearly sediment totals (kg), and yield (kg m^{-2}) from sidecast measured on selected plots below Fern Flat Road[1]

Year	Plot 2 Control Total	Plot 2 Control Yield	Plot 3 D.fir Total	Plot 3 D.fir Yield	Plot 11 D.fir Total	Plot 11 D.fir Yield	Plot 16 Grass Total	Plot 16 Grass Yield
1981	6.4	3.1	61.1	3.1	226.3	11.3	91.5	4.6
1982	5.9	2.5	49.9	2.5	47.9	2.4	4.1	0.2
1983	3.9	1.7	23.5	1.2	27.3	1.4	1.0	<0.1
Total	14.2		134.5		301.5		96.5	
Average	4.4	1.2	44.8	2.2	100.5	5.0	32.2	1.6

[1] based on FRI unpublished data

TABLE 4—Yearly sediment yields for given contributing surfaces at all plots (kg m^{-2})

	Kyfiuks Road					Herring Road	
Year	Plot 1 Road surface only	Plot 1 Cutbank	Plot 2 Road surface, drainage ditch and cutbank	Plot 3 Road surface, drainage ditch and cutbank	Plot 4 Road surface, drainage ditch and cutbank	Plot 1 Road surface, drainage ditch and cutbank	Plot 2 Road surface, drainage ditch and cutbank
1986	1.7	15.2	2.8	2.0	*	*	*
1987	0.8	7.0	4.0	2.0	14.2	1.7	*
1988[1]	0.3	5.2	2.2	1.5	8.5	2.5	1.6
Average	0.9	9.1	3.0	1.8	11.3	2.1	1.6

[1] January to August

DISCUSSION

The sediment yields calculated at the plot level are extended here to the entire forest road network in granite in an attempt to estimate the total contribution of sediment from this source. Because of the many assumptions in this exercise the figures arrived at remain very tentative. They are, however, believed to be at least in the right order of magnitude.

Yields at the Time of Peak Road Construction

From Table 4 the average annual contribution from the road surface-drainage ditch-cutbank combination after grading is estimated at 3 kg m^{-2} yr^{-1}. That from fresh sidecast is thought to be about 2 kg m^{-2} yr^{-1} (Table 3).

A simple weighting procedure using the frequency of road gradients in various classes was adopted to account for the likelihood of more sediment being generated on steeper road sections (Table 5). The gradient class of 2–4° is taken as the starting point since it includes the gradient of Plot 2 on Kyfiuks Road (3.5°). The average yield for Plot 2 (3 kg m^{-2}) has been halved for gentler slopes and doubled for steeper slopes. A comparison of the yields for Plots 2 and 4 on Kyfiuks Road suggests that this procedure can be adopted as a rule of thumb. Using these calculations, the annual post-construction yield from the surface of the 209 km of granite road amounts to 6800 t (Table 5).

The above approach makes no allowance for length of slope on sediment yield. Field plot experiments on agricultural soils have shown that the build-up of runoff depths and velocities on long slopes results in the loss of more material than on shorter ones. Zingg (1940) examined the effect of length and also degree of slope on soil loss from runoff plots at several mid-western United States experimental stations. He found that doubling the slope length caused a three-fold increase in soil loss whereas doubling the degree of slope increased soil loss 2.6 times. These figures were applied to the measured yield from Plot 2 on Kyfiuks Road and extrapolated via the road survey information to the forest road network in granite. Although the plot length is 25 m, the contributing road length used in the calculations is 100 m, which is the average distance between culverts. Based on these figures the annual sediment yield from the road surface was estimated at 6100 t, which is close to the total of 6800 t listed in Table 5.

Sidecast fill is capable of yielding an average of 2 kg m^{-2} each year for the 2–3 years after construction, and since it extends on average 10 m downslope the total annual production from this source is estimated at 4200 t.

To the above totals have to be added that for fine sediment (silts and clays) removed in suspension. The average of the suspended [illegible] concentrations calculated from the [illegible] collected at Plot 2 on Kyfiuks Road was 1.5 g l^{-1}. [illegible] relating this figure to the total volume of runoff from the plot over the length of the study, the amount of fine material removed in suspension from the surface can be estimated at 38 kg yr^{-1}. If this is extrapolated to the total road network in granite, the road surface can be expected to contribute an extra 400 t or 6% of the coarse sediment total. No data are available on the quantity of fine material produced from sidecast, but if the same proportions apply it could amount to 250 t. Thus, approximately 11,000 t of sediment (52 t km^{-1} of road, or just under 100 t km^{-2} of forest) could have been lost through

TABLE 5—Estimates of sediment production from road surfaces in Golden Downs and Motueka Forests, according to road gradient classes

Class	Yield	G.Downs	Motueka	Road length		Contributing surface area	Amount
degrees	(kg m^{-2})	(No. of gradients observed[1])		(km)	(%)	(m^2 × 10^3)	(t)
0–2	1.5	54	58	56	27	257.6	386.4
2–4	3.0	56	51	50	24	230.0	690.0
4–6	6.0	37	58	44	21	202.4	1214.4
6–8	12.0	37	37	36	17	165.6	1987.2
8–10	24.0	16	33	23	11	105.8	2539.2
				209		961.4	6817.2

[1] based on measurements taken at 0.5 km intervals

surface erosion each year from the road network on granite during the peak construction period in the late 1970s.

A further indication of how much sediment newly constructed forest roads in the granite terrain of Golden Downs Forest might produce is provided by Mosley (1980). He measured the volume of erosional features such as slumps, rills, and gullies in exposed road sections to estimate erosion rates in the Dart River area (Fig. 1). Most of the roads he surveyed were less than 2 years old. The total annual input from the 25 km of road was estimated at 12,000 t yr^{-1}. This converts to 700 t km^{-2} of roaded forest area per year, which is seven times higher than that estimated for the entire granite area of the two forests in the present study.

The higher totals in Mosley's (1980) study may reflect the inclusion of mass movement phenomena as well as those derived from surface erosion in his calculations. The present study considers only sediment mobilised by surface erosion. If the maximum values recorded here (14.2 kg m^{-2} in 1987 at Plot 4 on Kyfiuks Road, and 11.3 kg m^{-2} at Plot 11 on sidecast in 1981) are extended to the forest-wide road network, a figure of 40,000 t or 320 t km^{-2} of forest is arrived at for annual sediment production from newly formed road surfaces. It must be recalled, however, that within any forest, road construction is carried out over a long period. Thus, it is questionable whether a figure of this magnitude would be achieved. Even if it was, only a fraction of the material would find its way into nearby streams and gullies through surface erosion alone. Much of that derived from sidecast fill, for example, would simply be transferred further downslope or perhaps become dispersed across areas lying between major tributary streams. A similar situation was reported by Megahan *et al.* (1986) in Central Idaho. Four months after sidecasting, material dislodged by erosional processes had only moved an average of 6 m. Exceptions are always likely where highly localised rainstorms with return periods exceeding 5 yr trigger mass movement phenomena such as debris slides on deep, unconsolidated fill. These may enter local water courses with devastating consequences, and in so doing account for the shortfall in specific yields seen in the present study compared with Mosley's estimates.

Current Yields

Information on surface durability collected during the road survey suggests that roughly 40% of the cutbank surface area is now stable and not contributing much sediment to the drainage ditch. This was confirmed by observations that very little material is now stored in drainage ditches. At the present time then, the road surface itself may be a more important source of sediment than the cutbank. On the basis of the yield data from the Herring Road site (not graded), and the apparent stability of the cutbanks in both forests, the current production of sediment from the cutbank-drainage ditch-road surface combination is estimated at 3000 t yr^{-2}. Average yields calculated for sidecast at Fern Flat Road decreased markedly over the 3-year study period from 6 kg m^{-2} in 1981 to 0.8 kg m^{-2} in 1983. Assuming the 1983 figure to be more representative of the present conditions, the current annual yield from sidecast is estimated at 1700 t. This gives a total for the present road system in granite of 4700 t (37 t km^{-2}) per year.

Potential Yields at Time of Harvesting

If the plantings in granite in the two forests were all harvested at about the same time, the current road density of 16 m ha^{-1} could require doubling, and many of the existing roads would need to be upgraded. The present yearly sediment production figure of 4700 t for surface erosion could then conceivably rise to well over 20,000 t (160 t km^{-2}) per year. Whether a yield of this magnitude was ever achieved would depend on the harvesting schedule adopted.

Natural or Background Rates of Erosion

The effect of the presence of roads on sediment supply to local stream courses and neighbouring rivers can only be appreciated by comparing yields from these sources with those from undisturbed areas. However, such comparisons are difficult, first because of the lack of information on background or natural rates of erosion, and secondly because there are no data available on how long sediment from roads may remain in storage before entering major waterways. In addition, information available on local erosion rates is indicative of sediment delivery from the catchment and not sediment supply and storage. These points should be kept in mind in the subsequent discussion.

From data supplied by Adams (1980), annual bedload transport rates for rivers in the southwest Nelson area are estimated to be somewhere between 30 and 100 t km^{-2}. No data are available for suspended loads in local rivers, but information contained in maps prepared by Adams (1980) suggests that they range between 300 and 500 t km^{-2} per year. Mosley (1980) concluded that the natural sediment yield for the Dart River area in Golden Downs Forest, was 9600 t yr^{-1}, which converts to 120 t km^{-2} yr^{-1}. Thus the annual natural erosion rate for southwest Nelson lies somewhere between 100 and 600 t km^{-2}. Given the erosion-prone nature of the Separation Point granite, a figure towards the upper end of this range ($\simeq$ 500 t km^{-2}) may be more representative.

Management Implications

The results of this study have some important implications for the management of forest roads in the granite terrain. Grading as a part of any road management plan should be kept to a minimum to avoid rejuvenating sediment production. The aim of grading should be to ensure adequate surface drainage rather than disturb semi-stable vegetation and gravel. Any attempts to improve the efficiency of roadside drainage ditches by excessive grading may increase sediment delivery rates to local gullies in the short-term. After storms, all material derived from cutbank collapse should be removed from the drainage ditch to avoid rutting of the road surface, and culvert blockage or by-pass.

Ridge-top roading should be implemented where possible, as it supplies two slopes to dispose of sidecast and runoff. Minimum sideslopes should be chosen for roads where ridge-top routes are not practicable. This will keep cutbanks small and reduce the volume of sidecast material.

CONCLUSIONS

The major sources of sediment in the immediate post-construction period were most likely derived not from the road surface, but from the cutbank, drainage ditch, and sidecast fill near streams and gullies. The fresh cutbank surface is highly prone to disturbance not only by surface runoff, but also by needle-ice activity in winter, which may contribute significantly to sediment totals in the first few years after construction or upgrading. Material from the cutbank quickly accumulates in the drainage ditch, with only minor amounts being removed by surface runoff and overland flow during small-to-moderate storms. This accumulation process gradually diminishes as the exposed granite regolith on the cutbank becomes stabilised by surface hardening and vegetation growth.

The lower yield measured on Plot 3 at Kyfiuks Road was unexpected. Without a protective layer of gravel on the surface, this plot should have been more prone to erosion than its counterparts with gravel. It appears that the sandy granite regolith promoted rapid infiltration during storms, and on only a few occasions was there evidence of significant surface runoff in the form of rills and micro-channels. It is unlikely, however, that this situation would have persisted on steeper slopes, where thresholds of sediment mobility would be much lower and yield rates accordingly higher. Nor would it be safe to assume that the practice of applying gravel to roads with gentle gradients in granite terrain should be abandoned. A surface devoid of gravel would be much more prone to rutting by vehicular traffic, which would in turn promote further surface erosion.

The results from the Fern Flat Road study demonstrate that, at least in the early stages, an introduced vegetation cover on sidecast fill was no guarantee that sediment supply from sidecast fill would be reduced. However, in the longer term, the growth and expansion of scrub over the sidecast surface, and the tendency towards surface hardening, reduce the ability of the fill to yield large amounts of sediment.

Surface erosion of the granites may have been responsible for annual sediment production rates as high as 40,000 t (320 t km^{-2}) around the time of peak road construction, but present rates are an order of magnitude below these. Predicted levels of sediment production arising from future road construction and upgrading in the two forests could potentially rise to 20,000 t (160 t km^{-2}), but again a yield of this magnitude would be dependent upon most of those compartments planted in granite being ready for harvesting within a few years of each other. In addition, the actual quantities of sediment mobilised by surface erosion over the relatively small proportion of the forest area involved in the road network may not be particularly significant when compared with the total quantity from geologic erosion.

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