SOIL RESOURCES OF THE MARLBOROUGH SOUNDS AND IMPLICATIONS FOR EXOTIC PRODUCTION FORESTRY

2. Potential Site Disturbance and Fine Sediment Production from Various Forest Management Practices

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ABSTRACT

Regoliths (mantle of soil and weathered rock) on hilly and steep land in the Marlborough Sounds were rated as sources of fine sediment based on texture, thickness and erodibility. Erodibility was assessed by comparing measurements of macroaggregate and microaggregate stability with very highly erodible soils from the Wither Hills near Blenheim, and Kaiteriteri near Motueka. The potential impacts of alternative forest management practices on site disturbance were also assessed in relation to major slope classes. For steep slopes, ratings of potential impacts on fine sediment production were then made in relation to ratings of sources of fine sediment for the main regolith types.

Erosion of thick (≥1 m) regoliths occurring below 200 m is likely to yield the most fine sediment. Ratings of potential impacts resulting from forest management practices are also greater on these regoliths, particularly for management practices which cause most site disturbance. Such practices include access tracks, firebreaks, scrub-raking, and line-dozing during forest establishment, and tractor-skidding and cable-skidding methods of forest harvesting. To minimise impacts from harvesting operations on hilly and steep land in the region it is recommended that alternative methods of log extraction such as skyline, balloon and helicopter logging be investigated.

INTRODUCTION

Land use practices on hilly and steep land often disturb and scar the ground surface, and expose material that is vulnerable to erosion. Materials transported from these sources by fluvial

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erosion and/or mass movement, are deposited to form sediments in the Marlborough Sounds.

The history of land use in the Marlborough Sounds has been outlined briefly in Part 1 (Laffan and Daly, 1985). The clearance of the original indigenous forest over large areas of the region undoubtedly caused significant site disturbance and sediment production, mainly from mass movement and channel erosion. Forest cover is widely acknowledged as a stabilising influence on the soil but stability can be lost in production forests by site disturbances resulting from management practices. Renewed site disturbance and increased sediment production resulting from exotic afforestation have already been recorded at some localities in the Marlborough Sounds. Elsewhere in New Zealand and overseas the impact of production forestry in causing increased soil erosion and decreased water quality has been well documented (Montgomery, 1976; O'Loughlin, 1979; Hauge *et al.,* 1979); Swanston, 1981).

Recent investigations of the marine environment near Farnham Forest in the Marlborough Sounds indicate that logging of the forest has caused increased soil erosion and accumulation on the near-shore seabed with mainly silt- and clay-sized sediments (Johnston *et al.,* 1981). Studies of sediment concentration adjacent to Farnham Forest and of laboratory flocculation processes in sea water (O'Loughlin, 1980) suggest that sedimentation of suspended particles is likely to proceed rapidly in near-shore environments in the Marlborough Sounds. This has important implications for water quality and accumulation of sediments on the seabed. Although any impact of decreased water quality from suspended sediments may therefore only be short term, the impact on sedimentation may be long term, particularly in regard to marine life and navigation in shallow inlets.

The Marlborough Sounds region is particularly sensitive to land use changes because of its unique physical features. The partly drowned landscape is characterised by steep slopes which commonly extend below sea level. Even small catchments frequently discharge directly into the sea, while floodplains and other channel features capable of significant sediment storage are confined mainly to the heads of the larger bays. Consequently, over much of the region the marine environment is highly sensitive to changes in catchment hydrology and soil erosion.

Proposals for exotic forestry over large parts of the region make it important to assess the potential impacts of forestry on the production of fine sediments (*i.e.,* <2 mm). Clay (<2 µm)- and silt (<63 µm)-sized particles and small aggregates composed of them are particularly easily transported by fluvial action and are thereby added to the sediment in the Sounds. Awareness of the potential impacts from various management practices will be of considerable value in the planning and execution of forest activities in the region, especially where used in conjunction with soil information.

METHODS

Soil erosion is a complex process depending on the interaction of many factors including climate, topography, vegetation and land use in addition to inherent soil properties. In the Marlborough Sounds the production of fine sediment from forest management practices is expected to occur mainly from sheet, rill and subsequent stream erosion of exposed regoliths on steep slopes during moderate and heavy rainfall events. The fine sediments deposited on the seabed adjacent to Farnham forest are attributed mainly to these kinds of erosion of bare ground formed by tracks, cable-skidding of logs, and yarding areas (Johnston *et al.,* 1981). The amount of sediment movement depends on the erosivity of raindrops and running water, and the erodibility of the regolith (mantle of soil and weathered rock) material. Most of the indices of erodibility that have been developed are based on properties affecting soil dispersion, aggregate stability and the transmission of water (Gerrard, 1981).

For this study ratings of regolith erodibility were derived from tests of macroaggregate and microaggregate stability carried out on representative soils from the Marlborough Sounds and from the Wither Hills near Blenheim and Kaiteriteri near Motueka. Wither hill soil and Kaiteriteri hill soils (N.Z. Soil Bureau, 1968) are known to be relatively very highly erodible (Gibbs, 1945; Laffan and Cutler, 1977) and they were sampled for comparative purposes. The soils from the Marlborough Sounds were sampled from saprolites (rocks weathered *in situ*) and thick slope deposits derived from greywacke and schistose greywacke parent rocks. The slope deposits were sampled from three altitudinal zones — <200 m, >200 m <550 m and >550 m — which coincide with major climatic and weathering zones recognised in the Marlborough Sounds (Laffan and Daly, 1985). Because of their limited distribution in the region, regoliths from basic volcanic rocks and serpentine were not sampled. The soils from the Wither Hills and Kaiteriteri are formed from greywacke loess and derived slope deposits and from granitic saprolite, respectively.

The main regolith types in the Marlborough Sounds were rated qualitatively as sources of fine sediment based on thickness, texture and relative erodibility. The potential impacts of various forest management practices on site disturbance and fine sediment production were then assessed qualitatively in relation to the major regolith types.

Macroaggregate stability was measured by wet sieving (Gradwell and Birrell, 1979). Air-dry aggregates 3.3-2.0 mm in diameter were tested on a rack of sieves with mesh diameters 2.0, 1.0 and 0.5 mm. Results were expressed as a weighted mean diameter of water-stable aggregates. Aggregates with larger mean diameter are more water stable than those with smaller mean diameter.

Microaggregate stability was measured using mechanical shaking of the soil in suspension in water for 15 minutes followed by size analysis using a combination of a mild wet sieving method (Russell and Tamhane, 1940), for aggregates and particles $>63\ \mu m$, and an X-ray sedigraph method (Hendrix and Orr, 1970), for finer entities. In order to assess the relative contribution of aggregates and particles to each size fraction, a size analysis of the same sample was carried out following chemical treatments to destroy both organic and inorganic aggregating agents. The results were expressed as a dispersion ratio (Middleton, 1930) measured at the silt/sand boundary ($63\ \mu m$) and the clay/silt boundary ($2\ \mu m$). These ratios give the degree of aggregation of silt and clay particles into sand and larger size aggregates [$D(63\ \mu m)$] and of the degree of coagulation or flocculation of clay particles into silt and larger entities [$D(2\mu m)$].

Maximum possible degree of aggregation is given by D values of 0.0, while the absence of any aggregation or flocculation is given by $D=1.0$. Because aggregate stability is strongly influenced by organic carbon content (Luk, 1979), samples were measured for organic C% by the method of Blakemore *et al.* (1981).

RESULTS AND DISCUSSION

Regoliths as Sources of Fine Sediment

Sources of fine sediment (<2 mm) are determined primarily by the texture, thickness and erodibility of regoliths. Thick deposits of fine materials which are highly erodible comprise major sources of sediment. Conversely, thin deposits of fine materials or thick, very stony materials with low erodibility comprise relatively minor sources of fine sediments.

Texture and Thickness of Regoliths

Regolith is defined as the cover of unconsolidated material on the surface of the earth's crust (Fairbridge, 1968). It includes the soil profile as well as any unconsolidated material below. In the Marlborough Sounds regoliths consist of residual materials, some of which are very strongly weathered to saprolite, and various kinds of transported materials grouped broadly as slope deposits. The main regolith types and their relative abundances are given in Table 1.

TABLE 1: MAIN REGOLITH TYPES AND THEIR RELATIVE ABUNDANCE

*Type**	*Thickness*	*Abundance*	*Altitudinal Distribution*
A. Saprolite	>1 m	minor	<200 m
B. Thick slope deposits with <35% stones throughout.	≥1 m	abundant	all altitudes
C. Thick slope deposits with <35% stones in upper 1 m and >35% stones below 1 m.	>1 m	common	>200 m
D. Moderately thick slope deposits with <35% stones throughout.	50 cm–1 m	common	all altitudes
E. Thin slope deposits with <35% stones throughout.	≤50 cm	minor	all altitudes
F. Thick slope deposits with >35% stones throughout.	≥1 m	minor	mainly >200 m

*Derived from greywacke or schist only.

At altitudes below about 200 m, regoliths are formed mainly from strongly and very strongly weathered rocks, while at altitudes above 200 m regoliths are derived from weakly or moderately weathered rocks. The degree of weathering is clearly shown by the type and content of clay minerals. At altitudes below 200 m, regoliths are dominated by kaolinitic clay minerals, indicative of strong weathering, and at higher altitudes by micaceous clay minerals, indicative of relatively weak weathering (Laffan *et al.*, in press).

Regolith thickness is highly variable, particularly for slope deposits at altitudes above about 200 m, but it is related partly to landform position and rock type. Thicknesses up to 10 m have been observed in relict periglacial deposits (Laffan, 1980) which occur on side slopes or concave depressions. Shallow regoliths (< 50 cm thick) commonly occur on ridge and spur crests in association with rock outcrops, and occur extensively on ultramafic rocks. Elsewhere, regolith thicknesses > 1 m occur widely.

Thickness of topsoil is also highly variable. The mean topsoil thickness at 318 sites under scrub or grassland was 13 cm with a range of 0-52 cm. At 55 of the sites (17% of total) there was no topsoil present, while only 7 sites (2% of total) had topsoil thickness > 25 cm. Topsoil thicknesses < 10 cm occur mainly under scrub.

The particle size of the regolith is variable, particularly at depths below 1 m. Stone (or gravel) content in the upper 1 m of slope deposits varies mainly from few (< 5% stones by volume) to abundant (35-75% stones by volume), but on average few to many (< 35%) stones occur. At depths below 1 m stone content varies from few (< 5%) to profuse (> 75%). Slope deposits with stone content < 35% at depths below 1 m occur widely at all altitudes in the region. Stone content > 35% at depths below 1 m are generally associated with stratified relict periglacial deposits (Laffan, 1980) which occur relatively extensively at altitudes above 200 m throughout the region. Regoliths with abundant or profuse stones throughout their total thickness are associated with some relict periglacial deposits and deposits adjacent to drainage channels, but their overall occurrence is relatively minor. Saprolites generally have only few (< 5%) stones throughout and, though their total area is small, they occur commonly at altitudes below about 200 m.

Throughout the Marlborough Sounds the fine earth fraction (< 2 mm) in the upper 1 m is dominated by silt (0.05-0.002 mm) and clay (< 0.002 mm). Particle size analysis of 36 profiles from hilly and steep land predominantly gave silt values in the 35-55% range and clay values in the 25-45% range in the upper 1 m.

Erodibility of Regoliths in Relation to Aggregate Stability

Although aggregate stability tests do not make allowance for soil materials already disaggregated by natural or human disturbances, or for entrainment of soil materials during slope wash, they can give an indication of relative erodibility of soils (*e.g.*, Bryan 1976; De Vleeschauwer *et al.*, 1978; Chhetri, 1971; Summer, 1982).

TABLE 2: RESULTS OF MACROAGGREGATE AND MICROAGGREGATE STABILITY TESTS AND RATINGS OF ERODIBILITY FOR SOILS FROM THE MARLBOROUGH SOUNDS, WITHER HILLS AND KAITERITERI

Sample Site No.	*Regolith Type*	*Location Grid Ref.*	*Altitude (m)*	*Sample Depth (cm)*	*Organic C%*	*Macroag. Stab. Ave. Aggre. diam. (mm)*	*Microag. Stab. Dispersion Ratios*		*Rating of Erodibility**
							D (63 µm)	*D* (2 µm)	
1	Saprolite	Tennyson Inlet	30	12–30	2.45	2.2	0.8	0.1	M
	(>1 m)	S15 060468		40–70	0.75	1.4	0.8	0.3	H
2	Saprolite	Port Underwood	30	90–120	–	–	0.9	0.6	H
	(>1 m)	S22 411258							
3	Saprolite	Port Underwood	35	0–15	3.78	1.7	–	–	M
	(>1 m)	S22 428266		35–60	0.70	1.2	–	–	H
4	Thick (1 m)	Port Underwood	150	0–10	3.0	1.7	0.5	0.4	M
	slope deposits	S22 431262		13–48	0.79	1.2	–	–	H
	with <35% stones			48–90	0.38	1.2	0.8	0.3	H
5	Thick (>1 m)	Port Underwood	380	0–10	5.41	2.1	0.6	0.3	L–M
	slope deposits	S22 435269		12–58	2.30	2.4	0.7	0.4	L–M
	with <35% stones			86–110	0.54	1.8	0.6	0.1	M
6	Thick (>1 m)	Port Underwood	580	26–50	2.97	2.2	0.4	0.1	L
	slope deposits	S22 442272							
	with <35% stones								
7	Thick (>1 m)	Tennyson Inlet	400	25–70	2.48	2.3	–	–	L
	slope deposits	S15 053451		70–100	1.70	2.3	0.8	0.0	L–M
	with <35% stones								
8	Thick (>1 m)	Wither Hills	75	0–13	1.63	1.8	–	–	M
	loess plus	S28 227944		26–55	0.35	1.1	1.0	0.7	VH
	derived slope			72–100	0.20	1.6	0.8	0.5	H
	deposits			140–180	0.15	1.0	0.9	0.8	H
				190–200	0.12	1.0	1.0	1.0	VH
9	Saprolite	Kaiteriteri	300	0–20	2.39	1.7	–	–	M
	(>1 m)	S14 365576		20–54	0.70	1.2	0.7	0.1	M–H
				54–96	0.32	1.0	1.0	0.1	VH
				145–170	0.12	1.0	1.0	0.0	VH

* Erodibility ratings based on:
Low (L): >2.0 mm average diameter and *D* (63 µm) ratio 0.0–0.4
Medium (M): 1.6–2.0 mm average diameter and *D* (63 µm) ratio 0.5–0.7
High (H): 1.2–1.5 mm average diameter and *D* (63 µm) ratio 0.8–0.9
Very High (VH): <1.2 mm average diameter and *D* (63 µm) ratio 1.0

Table 2 gives organic carbon (%C) values and the results of macro- and microaggregate stability tests for soils from the Marlborough Sounds, Wither Hills and Kaiteriteri. The results of macro- and microaggregate stability tests show similar trends. Both tests show that the subsoils from the Wither Hills and Kaiteriteri have significantly lower stability ratios than subsoils from the Marlborough Sounds. Comparison of all samples shows that topsoils are generally more stable than subsoils, and probably reflects the higher organic carbon content of topsoils relative to subsoils. Results for the Marlborough Sounds indicate that subsoils from altitudes below 200 m generally have lower aggregate stability than subsoils from higher altitudes. The lower stability at lower altitudes is at least partly attributable to the relatively low organic C%. However, purely kaolinitic flakes have been shown to exhibit severe slaking (Emerson, 1964), so it is possible that the high kaolinite contents of samples from lower altitudes (Laffan *et al.*, in press) could have affected the observed decrease in aggregate stability of these samples. Conversely, subsoils at altitudes above 200 m in the Marlborough Sounds have relatively high organic C% and low contents of kaolinite. Further work at the New Zealand Soil Bureau aims to provide an explanation of the relative stabilities of the soils in terms of their constituents. Relevant constituents probably include clay minerals and organic matter and also iron oxides. iron oxides exist as discrete particles and a high dispersibility means of strong association with clay minerals such as kaolinite (*e.g.*, Krishna Murti *et al.*, 1977). Nevertheless well crystallised iron oxides exist as discrete particles and a high dispersability results from the unassociated mixture of oxides and clay minerals (*e.g.*, Deshpande *et al.*, 1968). Clearly, then, the crystallinity of the iron oxides in these soils merits further study.

The high values of $D(2\ \mu m)$ for the subsoils from the Wither Hills show that they are highly dispersed and lack any effective aggregation of clay particles into larger units. In contrast, subsoils from Kaiteriteri and from altitudes above 200 m in the Marlborough Sounds have low to very low values of $D(2\ \mu m)$ indicating that the clays are aggregated into silt-sized or larger units. The intermediate values of $D(2\ \mu m)$ for subsoils from altitudes below 200 m in the Marlborough Sounds suggest that dispersion of clay particles is significant in these samples.

Overall assessment of the macro- and microaggregate stability studies suggests that subsoils from the Marlborough Sounds are more highly aggregated after being wet-sieved and hence less likely to be eroded than subsoils from the Wither Hills or Kaiteriteri. However, within the Marlborough Sounds, subsoils from altitudes below 200 m are less aggregated after being wet-sieved and hence more erodible than subsoils from higher altitudes. The microaggregate stability tests also suggest that in the Marlborough Sounds there is a tendency for the clay sized particles to flocculate into silt-sized particles in water, particularly in subsoils from altitudes above 200 m. Although regoliths in the Marlborough Sounds have been sampled only to 1.2 m, it is likely that materials at greater depths would have similar aggregate stability to overlying materials, particularly for regoliths with <35% stones throughout. It is also considered that the results for the Marlborough Sounds samples are representative of most regoliths in the region formed from greywacke or schist with <35% stones.

In Table 2 all the samples have been qualitatively rated for degree of erodibility based on the results of aggregate stability. They have been assessed relative to a very high rating of erodibility for the deepest soil horizons from the Wither Hills and Kaiteriteri. Their erodibilities are rated low, medium or high on

TABLE 3: RATING OF MAIN REGOLITH TYPES IN THE MARLBOROUGH SOUNDS AS SOURCES OF FINE SEDIMENT IN RELATION TO THICKNESS, TEXTURE AND ERODIBILITY

*Regolith Type**	*Altitudinal Zone (m)*	*Rating of Erodibility*†	*Rating for Sources of Fine Sediments*
Saprolite (>1 m)	<200	High	High
Thick (≥1 m) slope deposits with <35% stones	<200	High	High
	>200	Low–Medium	Medium
Thick (>1 m) slope deposits with <35% stones in upper 1 m and >35% stones below 1 m	>200	Low–Medium in upper 1 m probably low below 1 m	Medium–Low
Moderately thick (51–99 cm) slope deposits with <35% stones	<200	High	Medium–High
	>200	Low–Medium	Low–Medium
Thin (≤50 cm) slope deposits with <35% stones	<200	High	Low–Medium
	>200	Low–Medium	Low
Thick (≥1 m) slope deposit with >35% stones	>200	Not determined but probably Low	Low

* Derived from greywacke or schist only. † Based on mean subsoil ratings.

this basis only and might be rated differently in relation to other, less erodible soils. On this basis topsoils all have low to medium or medium erodibility ratings while subsoils of regoliths occurring at altitudes below 200 m have been rated as highly erodible. At altitudes above 200 m, subsoils have low, low to medium, or medium ratings of erodibility.

In Table 3 the main regolith types formed from greywacke or schist in the Marlborough Sounds have been rated as sources of fine sediment based on thickness, texture, altitudinal zone and erodibility. The slope deposits outlined in Table 3 also include residual regoliths formed mainly on ridge and spur crests by weathering of rock *in situ*. The erodibility rating is based on mean subsoil values from Table 2. Thick regoliths with <35% stones and high ratings of erodibility were given the highest rating as sources of fine sediment. Very thick (>5 m) saprolites have been observed in some road cuttings and they are likely to be greater sources of fine sediment than shallower regoliths. Conversely, thin (<50 cm) regoliths with <35% stones and thick regoliths with >35% stones and low or low to medium ratings of erodibility were given low ratings as sources of fine sediment. The results in Table 3 show that sources of fine sediment in the region are determined primarily by altitude, with major sources of fine sediment occurring at altitudes below 200 m and minor or medium sources occurring at higher altitudes.

Assessment of Potential Impacts of Forest Management Practices on Site Disturbance and Fine Sediment Production

Exotic production forestry includes a wide variety of management practices in the establishment, maintenance and harvesting of forests, which have varying impacts on site disturbance. For most management practices slope angle is a significant factor determining relative impacts on site disturbance. Management practices such as track or yard construction generally cause much greater site disturbance on steep slopes than on flat or rolling slopes. Impacts from other practices such as skyline or helicopter logging are probably largely independent of slope angle.

The greatest impact occurs from management practices which penetrate or remove topsoils and expose underlying materials. Such practices include excavations for roads and access tracks, firebreaks, yarding areas and tractor-logging tracks. Forest tracks, in particular, often cover a significant proportion of total for-

TABLE 4: POTENTIAL IMPACTS ON SITE DISTURBANCE OF SOME ALTERNATIVE FOREST MANAGEMENT PRACTICES IN RELATION TO MAJOR SLOPE CLASSES IN THE MARLBOROUGH SOUNDS

Slope Class	*Potential Impacts on Site Disturbance**							
	Establishment Practices					*Harvesting Practices*		
	Access tracks, firebreaks	*Burning-off*	*Scrub-raking*	*Line-dozing*	*Tractor-skidding*	*Cable-skidding*	*Skyline*	*Helicopter, balloon*
Undulating to rolling (3–12°)	M	L	L–M	M	M	L–M	L	L–VL
Moderately steep and moderately steep to steep (13–30°)	M–H	L	M	M–H	M–H	M	L	L–VL
Steep (31–38°)	H	L	M–H	H	H	M–H	L	L–VL
Very steep (>38°)	VH	L	†	†	†	H	L	L–VL
Relative time period of impacts	Long term	Short term	Short term	Short term	Medium-Long term	Short term	Short term	Short term

* VH = Very high impact
H = High impact
M = Medium impact
L = Low impact
VL = Very low impact
M–H = Medium to high impact
L–M = Low to medium impact
L–VL = Low to very low impact

† Slopes are generally too steep for safe or practicable operation.

ested area and intercept a relatively wide drainage area. Sediment sources arise from batters, track surfaces, and side castings. The importance of tracks or roads as sources of sediment is highlighted by the numerous studies showing high sediment yields from forest tracks (Swanston and Swanson, 1976; O'Loughlin, 1979; Graynoth, 1979). Other management practices which cause significant site disturbance include scrub-raking and line-dozing operations during forest establishment, and cable-skidding of logs during forest harvesting.

Management practices which cause minimal disturbance to the regolith include scrub-crushing and burning-off operations in the establishment phase, and skyline, balloon and helicopter-logging techniques during forest harvesting. Whereas in cable-skidding methods logs are partially lifted by a cable and dragged either wholly or partly along the ground surface, in skyline, balloon and helicopter methods, logs are lifted and transported clear of the ground surface thus minimising disturbance to the regolith.

Table 4 outlines a qualitative assessment of the potential impacts on site disturbance resulting from some typical management practices used in establishment and harvesting. Not all of the practices are used during a forest rotation as many are management options. The potential impacts have been assessed for sloping land (>3°) in relation to major slope classes 3-12°, 13-30°, 31-38°, >38°) used during the soil survey of the region. The assessments are based mainly on results of soil disturbance from various logging techniques (Rice, 1979; Schwab and Watt, 1981; Laffan, 1979). An estimate is also made of the relative time period over which the impacts on site disturbance are likely to occur (Table 4). For example, practices such as scrub-raking or line-dozing have impacts which are relatively short term because, once the forest is established, it eventually provides adequate ground cover to minimise the effects of site disturbance. On the other hand, practices such as access tracks and fire breaks are normally kept free of any vegetative cover and thus expose bare regolith materials over a relatively long term.

The potential impacts on fine sediment production from alternative forest management practices may be assessed from Tables 3 and 4. In Table 5 the potential impacts on fine sediment production have been assessed from the potential impacts on site disturbance on steep slopes modified according to regolith types and ratings as sources of fine sediment. The potential impacts shown in Table 5 have been assessed for slopes of 31-38°

TABLE 5: POTENTIAL IMPACTS ON FINE SEDIMENT PRODUCTION OF SOME ALTERNATIVE FOREST MANAGEMENT PRACTICES ON STEEP SLOPES IN RELATION TO REGOLITH TYPE IN THE MARLBOROUGH SOUNDS

Regolith Type	*Altitudinal Zone (m)*	*Rating for Sources of Fine Sediment*	*Potential Impacts on Fine Sediment Production**							
			Establishment Practices				*Harvesting Practices*			
			Access tracks, firebreaks	*Burning off*	*Scrub-raking*	*Line dozing*	*Tractor-skidding*	*Cable-skidding*	*Skyline*	*Helicopter, balloon*
Saprolite	<200	H	H	L	M–H	H	H	M–H	L	L–VL
Thick slope deposits with <35% stones	<200	H	H	L	M–H	H	H	M–H	L	L–VL
	>200	M	M–H	L	M	M–H	M–H	M	L	L–VL
Thick slope deposits with <35% stones in upper 1 m and >35% stones below 1 m	>200	M–L	M	L	M–L	M	M	M–L	L	L–VL
Moderately thick slope deposits with <35% stones	<200	M–H	M–H	L	M	M–H	M–H	M	L	L–VL
	>200	L–M	L–M	L	L	L–M	L–M	L	L	L–VL
Thin slope deposits with <35% stones	<200	L–M	L–M	L	L	L–M	L–M	L	L	L–VL
	>200	L	L	L	L	L	L	L	L–VL	VL
Thick slope deposits with >35% stones	>200	L	L	L	L	L	L	L	L–VL	VL

* H = High impact
M = Medium impact
L = Low impact
VL = Very low impact

M–H = Medium to high impact
M–L = Medium to low impact
L–M = Low to medium impact
L–VL = Low to very low impact

only, and they need to be reduced for gentler slopes and increased for very steep slopes.

Table 5 shows that greatest impacts on fine sediment production occur from forest management practices on thick regoliths at altitudes below 200 m. At altitudes above 200 m such practices have smaller impacts, particularly on thin or very stony regoliths. If the relative time period of impacts is also considered, then practices with long-term effects such as access tracks, firebreaks and tractor-skidding methods of logging will have the greatest overall impacts on fine sediment production.

Forest tracking and harvesting practices have often been linked with the initiation of mass movement erosion (O'Loughlin and Gage, 1975; Zeimer, 1981; Swanston, 1981). Evidence from New Zealand and overseas indicates that, to minimise landsliding under production forestry regimes, forest re-establishment should closely follow harvesting, and roads need to be carefully planned and constructed. Depending on size, landslides can cause significant site disturbance and production of fine sediments.

The incidence of both deep-seated and superficial forms of landslides in the Marlborough Sounds together with site factors involved in their initiation have been outlined (Laffan, 1980; Laffan and Daly, 1985). Exotic afforestation in the region should decrease the incidence of superficial landslides on natural slopes undisturbed by tracks or other excavations, provided that forest re-establishment follows closely after harvesting. Afforestation should also help stabilise land affected by deep-seated landslides. However, the impact of forest management practices on potential landslide incidence is likely to be significant where tracks or other excavations are constructed in saprolites, thick slope deposits with $<35\%$ stones, or where the bedrock is strongly shattered. Landsliding of batters in these materials is relatively common, particularly on steep slopes where batters are high, very steep and unbenched. Unconsolidated sidecastings from tracks and other excavations are also susceptible to mass movement and such track failures often produce large quantities of fine sediment.

CONCLUSIONS

The assessment of potential impacts of forest management practices on site disturbance and fine sediment production from different regolith types have important implications for exotic forestry in the region. Comparison of the different impacts will aid selection of appropriate management practices to minimise the overall environmental effects of exotic production forestry.

The results show that in the Marlborough Sounds the greatest impacts from forest management practices are likely to occur on thick regoliths at altitudes below 200 m. Particular care is therefore required in planning essential management practices such as access tracks and firebreaks on these regoliths, especially on very thick saprolites. Although the impacts are likely to be less on regoliths at altitudes above 200 m, it is important that management practices are used which minimise site disturbance at all altitudes. Management practices with minimal impact include burning-off during site preparation, and skyline, balloon and helicopter methods of log extraction. Although burning-off is used widely, the current preferred method of log extraction is cable-skidding. To minimise impacts from harvesting operations it is recommended that skyline, balloon and helicopter methods of log extraction be fully investigated.

Reduced site disturbance and fine sediment production will help preserve water quality and prevent adverse sedimentation of the seabed in the Marlborough Sounds.

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