117

SLOPE LIMITATIONS TO SUSTAINABLE LAND USE IN HILL COUNTRY PRONE TO LANDSLIDE EROSION

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Introduction

The identification and implementation of sustainable land use is currently a major challenge for land researchers and planners in New Zealand. Unfortunately this process is hindered by confusion about the meaning of sustainability. Many definitions exist and these tend to conflict because of different emphasis on either, biophysical (ecological), or socioeconomic aspects (Blaschke *et al.* 1991). The New Zealand Resource Management Act (1991) provides a useful definition, with the central concept being "managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their health and safety while: (a) sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; (b) safeguarding the life-supporting capacity of air, water, soil, and ecosystems; and (c) avoiding, remedying, or mitigating any adverse effects of activities on the environment". In agricultural systems, one aspect of resource management involves sustaining the biological and physical resources on which farm productivity depends, while at the same time minimizing detrimental effects to the environment. It is important, therefore, to identify those land use practices which lead to degradation of natural and physical resources.

One study in eastern Taranaki hill country (Blaschke *et al.*1992a, DeRose *et al.* 1993) identified sustainable land use classes on the basis of slope. These classes reflected increased slope instability after deforestation, and decline in potential pasture production caused by subsequent landslide erosion. This was a natural consequence of the relationship between landslide activity and slope angle which is well established in the literature on both theoretical (slope mechanics) and empirical grounds (Crozier *et al.* 1980). Hillslopes with an average slope above 28° were identified as being particularly prone to landslide erosion (DeRose *et al.* 1993, DeRose 1994). Further slope division was somewhat arbitrary, although slopes above 32° had a much higher landslide density, compared with the modal class of slopes between 28 and 32°. While these results have been particularly useful in helping to define land use sustainability on hard Tertiary sandstone lithologies (Blaschke *et al.* 1992b) they cannot be applied without qualification in other regions. This partly reflects the spatial limitations of extrapolating results from small experimental basins, but also reflects the fact that other adverse land use effects (i.e., nutrient runoff) may be as, if not more, important than landslide erosion. A classification of landforms based on nutrient runoff, for example, may not necessarily co-inside with a classification based on erosion potential.

Regional Councils now intend to adopt slope angles as a means of controlling land use activities on steep hill country (TRC 1993, MWRC 1993). This may be appropriate, but only once all aspects of sustainability have been considered, and where slope angles are based on sound research findings on the adverse effects of current land use activities. The purpose of this article is to review current information on the slope dependency of landsliding for other regions in the North Island.

Spatial patterns of landslide erosion

Hill country, below 1000 m in elevation, occupies over 40 % of New Zealand's land area (Blaschke *et al.* 1992a), and shallow landsliding has been recognised here as a major process leading to soil depletion, to decline in the productive potential of farmland (Lambert *et al.* 1984, Douglas *et al.* 1986, DeRose *et al.* in press), and to increased sediment and nutrient loadings in waterways. The density of shallow landslides is typically 3 to 10 times greater under pasture than under either native or exotic forests (Laffan 1979, Salter *et al.* 1981, Blaschke *et al.* 1992a, Hicks 1990, 1991, Hicks *et al.* 1993, DeRose *et al.* 1993, 1995, Phillips *et al.* 1990, Marden *et al.* 1989, 1992, Bergin *et al.* 1993, Marden and Rowan 1994). In specific situations, 20 fold increases in landslide density have been observed following deforestation (O'Loughlin and Pearce 1976). Increased landslide occurrence reflects decreased slope stability due to removal of the reinforcing strength of tree roots (O'Loughlin and Ziemer 1982), and due to changes in slope hydrology. These results are also consistent with sediment yields from paired catchments (Hicks 1988) and studies of long-term lake sedimentation (Page and Trustrum *in prep.*), which suggest increases in sediment production from drainage basins of 6 to 8 times under pasture.

Landslides tend not to be evenly distributed within regions, and are often clustered into 'families' related to specific triggering events. These are usually high intensity storms (Eyles and Eyles 1981) producing rainfall depths above certain critical threshold values (Crozier 1986) that vary according to local pre-conditions to failure. In a number of storm damage assessments, Hicks (1990, 1991) and Hicks *et al.* (1993) repeatedly demonstrated that the way in which landslide are distributed on hillslopes is much the same between different regions. That is, most hillslopes have little or no erosion, and progressively fewer hillsides have increasingly higher levels of erosion. In statistical terms this pattern of erosion follows a binomial distribution. Comparisons of rainfall depths to area eroded for individual storm events (Salter *et al.* 1981, Crozier 1986, Eyles and Eyles 1981, Eyles *et al.* 1978) show that, in general, the highest levels of erosion tend to correspond with storm centres where rainfall densities and totals were highest. Furthermore, site specific studies which have compared the same hillsides under different rainfall conditions (Eyles 1971, DeRose 1994) have shown that landslide densities tend to be higher in storms with higher total rainfalls. Page *et al.* (1994a) also inferred increasing erosion with increasing storm intensity from the thickness of individual sediment pulses, which showed good correlation with total rainfall for individual storms over the last 100 years.

Within areas that have had the same total rainfall, there is usually a great deal of variation in landslide densities, with intact hillsides interspersed among others that have eroded (Hicks *et al.* 1993). This variability can be attributed to the different susceptibility of individual hillslopes to failure. Controlling factors are likely to be those that influence slope stability by altering the balance between shear strength (resistance) and stress (shearing) forces (Crozier 1986). These include vegetation type (root strength), soil cohesion, internal angle of friction of soil, slope angle, weight of soil (depth, bulk density), and slope hydrology (development of pore water pressure) which is in turn controlled by drainage characteristics of the soil. Most landslides would be expected to occur in regions where soils are 'weakest' and prone to frequent soil saturation: on steep hillsides that are convergent in form, lacking a forest cover, are where soils are deep and underlain by rocks which weather to produce a regolith with low friction angle and soil cohesion when saturated. There are very few studies in New Zealand that have examined in any detail the relationship between landslide density and variation in critical factors for slope stability across a range of landforms, although the effect of root strength on slope stability has been investigated (O'Loughlin and Ziemer 1982, Phillips and Watson 1994). Some studies have examined in detail the relationships between slope form and landslide form and location (Eyles 1971, Blong 1974, Eyles *et al.* 1978, Crozier *et al.* 1980, DeRose *et al.* 1991, DeRose 1994). A larger number of studies (Selby 1979, Appendix 1) have measured the slope angle of landslide failures, but not all have measured a sufficient number, to construct slope distributions for large areas of hill country.

Slope frequency distributions

There is usually a well-defined limiting slope for a given set of lithological, soil, hydrological, and climatic conditions below which landslides do not occur. Figures 1, 2 and 3 show frequency distributions of slope angle for landslides (usually shear plane slope) which have been summarised from various surveys. These show that the limiting slope for landslide occurrence is between 18 and 24° for most areas of hill country in the North Island. Above this limiting slope, there is an increase in the frequency of landslides, reaching a maximum between 26 and 40°. The frequency distribution of slope for landslides is similar to that of slope for the hillslopes on which landslides occur (i.e., parent slope). Consequently, the decrease in frequency of landslides on steeper slopes reflects a decreasing proportion of these hillslopes within drainage basins, and there is usually an upper slope limit of between 50 and 60°. The mean slope of landslide distributions is typically between 29 and 39° (Appendix 1), with the notable exception of greywacke lithologies in the Wellington region (Lawrence *et al.* 1982). Slope angle distributions (Figs. 1 to 3) also show that few landslides occur at, or immediately above, limiting slopes. For the purpose of comparison between regions, it is more useful to consider a threshold slope above which 95% of landslides occur (Appendix 1). In this case most landslides occur on slopes above 20 to 33° for most hill country areas.

The majority of surveys investigating landslide slope have been conducted on pasture hillslopes, and while some have been conducted under forest (Pain 1968, Laffan 1979, Jane and Green 1983, Blaschke 1988), results are often not directly comparable because forested areas invariably remain on steeper landforms. Any difference in slope frequency distributions usually reflects a difference in the frequency distribution of parent slopes. For example, Pain (1968) showed that the mean slope for landslides was 4.4° steeper under forest, but indicated that forested areas were on steeper hillslopes. Similarly, Blaschke (1988) measured a steeper mean for landslides under forest compared with surveys by DeRose *et al.* (1993), but there was also a similar difference in the mean slope of hillslopes on which the surveys were conducted (Appendix 1). Hence, although landslide densities are clearly lower under a forest cover, there is no evidence to suggest that the slope distribution, or limiting slope, for landslides is any different between forested or pasture hillslopes.

The results summarized in Appendix 1, however, suggest that differences in slope distributions may relate to lithology. Landslides occur on gentlest slopes where hillslopes are underlain by soft Tertiary mudstone and sandstone lithologies. These rock types occur extensively along the east coast of the North Island and have been studied in the following catchments: Pakaraka (Crozier 1980), Tangoio (Eyles 1971), Lake Tutira (Page *et al.* 1994b), Otoi (Harmsworth *et al.* 1987), and Emerald Hills and Arai Matawai (in 't Veld and de Graaf 1990). O'Bryne (1967) considered that, on soft calcarious mudstone, serious slipping started on moderately steep slopes between 20 an 25°. Lowest overall slope angles have been measured for landslides triggered during Cyclone Bola, probably one of the most extreme rainfall events to occur this century. Mean slopes were 27.4°(in 't Veld and de Graaf 1990) and 30.6°(Page *et al.* 1994), and 95% threshold slopes were 18 and 21°, respectively, for landslides triggered during this Cyclone. Eyles (1971), whose survey at Tangoio included the 1938 ANZAC Day event (of similar recurrence interval to Cyclone Bola), measured a mean slope of 32.4°, and 95 % of landslides occurred on slope segments steeper than 24°. For less intense, more frequent storm events, mean slopes for landsliding range from 33°(Crozier 1980) to 36°

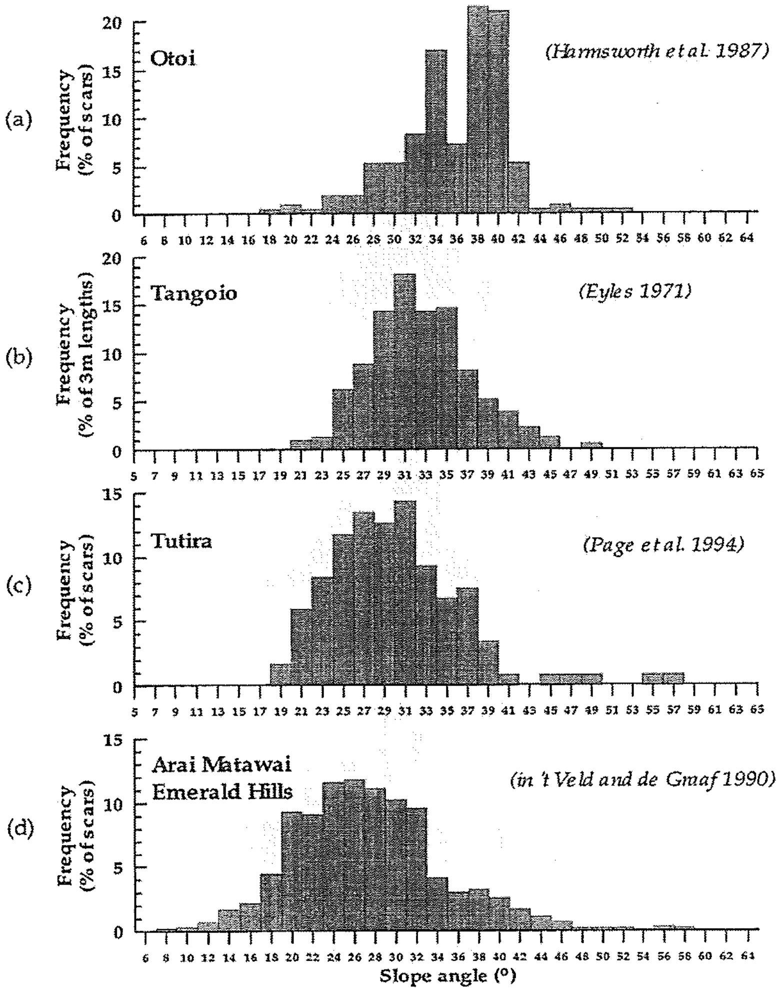

Fig 1: Frequency distribution of landslide slope angle on soft Tertiary mudstone and sandstone.

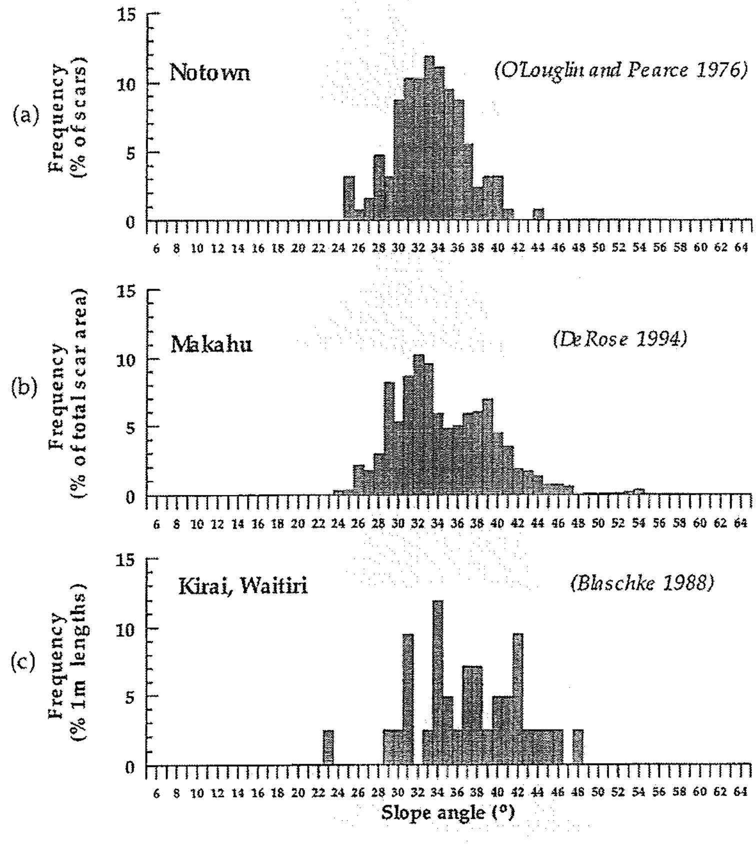

Fig. 2: Frequency distribution of landslide slope on hard Tertiary sandstone lithologies.

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underestimate the extent of landsliding on steeper hillslopes (>32°). However, landslide density information (Fig.4) confirms that slope frequency data (Fig 2b) can be used to establish approximate slope threshold conditions for landsliding, but suggests that further slope sub-division is somewhat arbitrary.

Similar conclusions can be drawn from other surveys. Eyles (1971) indicated an increase in the proportion (20 and 56 %) of hillslope profiles covered by landslide scars when slope increased from 24 to 30°. In addition, hillslope segments steeper than 30° had most of their length covered by landslide scars, suggesting a high density of landsliding. Salter *et al.* (1981) showed that the density of landsliding was greatest for 21-25°, and 26-35° slope classes. These results are not particularly useful, however, because of the broad slope intervals. Laffan *et al.* (1979) proposed a classification of landslide potential in the Charleston-Punakaiki region based on slope angle of landforms: flat to rolling hillslopes (0-12°) had a negligible or slight potential; moderately steep to steep hillslopes (13-30°) had a moderate potential; and steep and very steep hillslopes (>30°) had a severe to very severe potential for landsliding.

Conclusions

Previous research has established that landslide erosion in many areas of steep hill country is much more extensive on pasture hillslopes than under either exotic or native forests. The results summarized in this article, show that in addition, landslide erosion is confined to hillslopes above certain slope angles. While it is clear that hillslopes steeper than 30° are particularly prone to landslide erosion in most areas of hill country, hillslopes gentler than 20° remains largely unaffected, and hillslopes between 20 and 30° may have different landslide susceptibility, and resultant landslide densities, depending on the local soil and hydrological conditions that affect slope stability. In particular, threshold slopes for landsliding vary according to lithology as follows: above 20° on hillslopes underlain by soft Tertiary mudstone and sandstone, Miocene andesite, and deeply weathered greywacke; above 27-28° on hillslopes underlain by hard sandstone; and above about 33° on hillslopes underlain by hard greywacke. Where deep colluvial fills overlie greywacke rocks, the slope limitations may be similar to Tertiary lithologies.

In order to reduce soil erosion and mitigate the hazard from landsliding, reforestation of steep slopes should be considered as a preferred land use option. Landslide erosion, however, is only one aspect of sustainability in hill country, and all aspects of land management should be examined before considering slope angle as a means to regulate particular land use activities. The surveys summarised in this article, nevertheless, provide useful information about slope susceptibility to landslide failure that could help set guidelines for future effective sustainable land use in North Island hill country.

Slope defined sustainability criteria for landslide risk

Frequency distributions of landslide slope angle are by themselves insufficient for defining limitations to land use in steep hill country. Additional information is required about the density of landsliding in relation to slope angle of hillslopes, and this may not be apparent from frequency distributions for landslides alone. Unfortunately, very few surveys have measured this relationship. One example in Taranaki hill country (DeRose 1995), showed a linear increase in the average density of landslides on hillsides, with increasing mean slope above 27-28°. These results (Fig 4) suggest that frequency distribution of landslide slope angles (Fig. 2b) tends to over-estimate the extent of landsliding on the modal class (28-32°) of hillslopes, and greatly

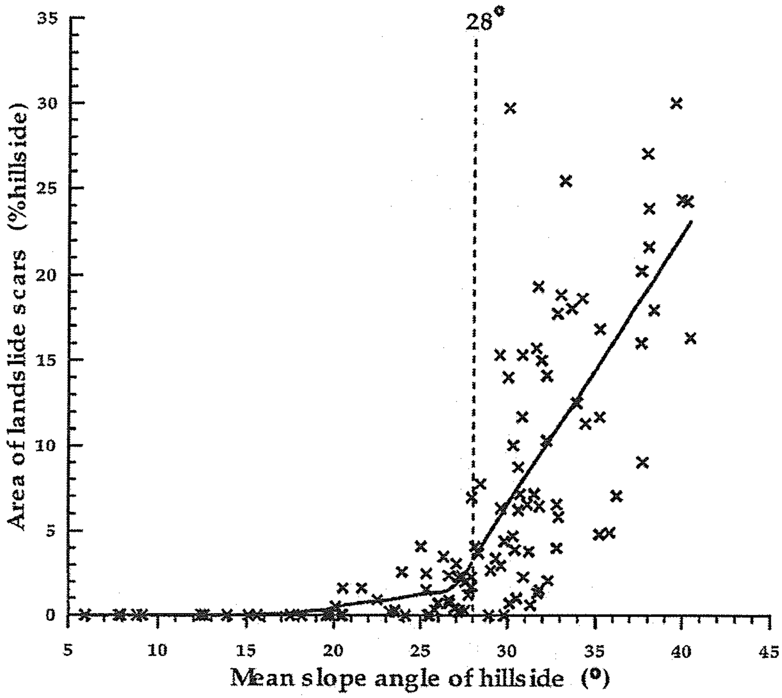

Fig. 4: Total area of contemporary landslide scars on hillsides of first-order drainage basins at the Makahu study site, plotted against mean slope. Solid line represents average trend.

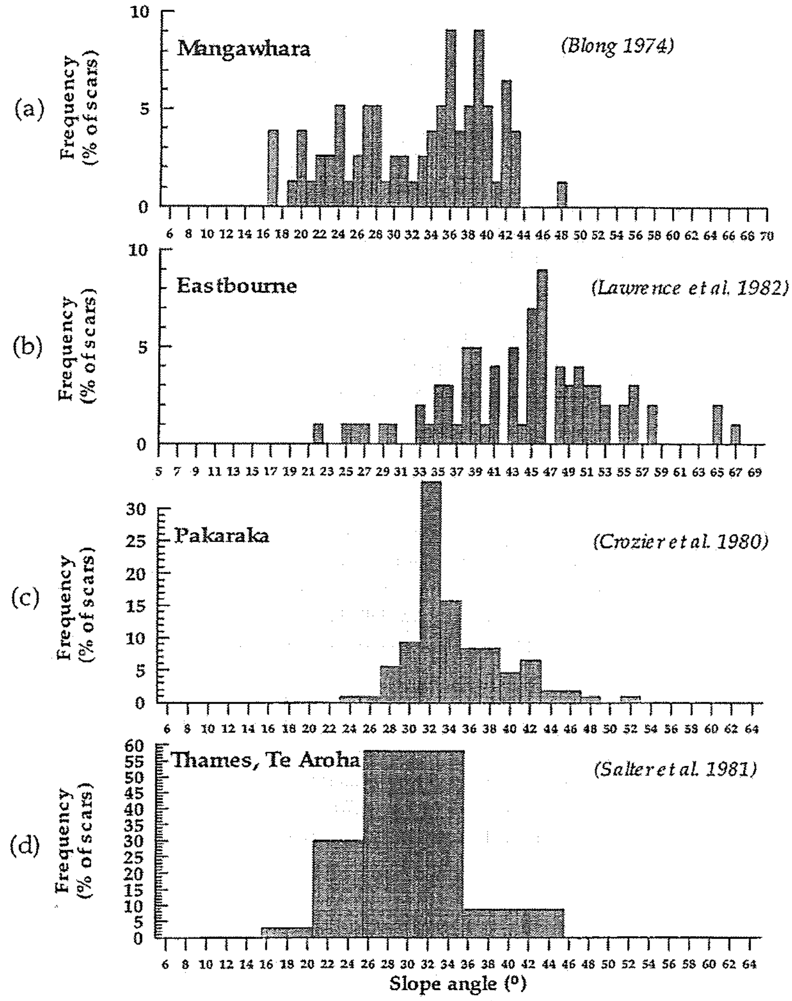

Fig. 3: Frequency distribution of slope angle for various lithologies: (a) weathered greywacke; (b) hard greywacke; (c) soft Tertiary mudstone/sandstone; and (d) Miocene andesite.

(Harmsworth *et al.* 1987), and threshold slopes range from 24 to 28°. Clearly, slope distributions of landslides relate to rainfall conditions, with the larger magnitude rainfall events producing a greater number of landslides on gentler slopes.

Slope angle distributions appear to be similar for crushed Cretaceous sandstones and alternating mudstone and sandstone lithologies. O'Loughlin and Zhang (1986) indicated that shallow debris slides and avalanches at Mangatu Forest occur predominantly on slopes over 25°. Phillips (1988) measured a mean slope of 35° for landslides in the Waitahaia catchment. The standard deviation for the slope distribution was 7°, suggesting that most landslides occurred above 21°.

On hillslopes underlain by hard Tertiary sandstone lithologies, landslides occur more frequently on steeper slopes when compared to softer lithologies (Fig 1). Mean slopes for landslides are 33 to 35° with 95 % of landslides occurring on slopes above 27-28°(DeRose 1994, O'Loughlin and Pearce 1976). The threshold slope for landsliding was found to decrease from 35 to 28° with increasing rainfall intensity (DeRose 1994) at Makahu.

Research on hillslopes underlain by hard Jurassic greywacke (Eyles *et al.* 1978, Lawrence *et al.* 1982) indicates, that although some landslides occur down to 20°, 95% of landslides occur on natural slopes (as opposed to cut and fill) above 33 to 36°, indicating an even steeper threshold slope compared with hard Tertiary sandstones. Mean slopes for landsliding were 44.5° in Eastbourne (Lawrence *et al.* 1982), and 49° in and about Wellington city (Eyles *et al.* 1978). Crozier *et al.* (1990), investigating the stability of colluvium-filled bedrock hollows in the Belmont area, found that slopes failed in CBDs where colluvial fills were deeper than 1.5 m and slope in most cases exceeded 25°. Where greywacke rocks are deeply weathered and have altered to clay rich regolith, landslides occur more frequently on gentler slope angles, and frequency distributions are more comparable with soft Tertiary lithologies (Fig. 3a). Mean slope for landslides vary from 28.6° (Pain 1968) to 34° (Selby 1976), and a threshold slope of 20° is interpreted from slope data in the Mangawhara Catchment (Blong 1974).

Few other lithologies have been investigated which yield suitable slope information. Salter *et al.* (1981) investigated landslide density on hillslopes underlain by predominantly weathered soft Miocene andesite over a large area in the Thames - Te Aroha region. Although slope intervals were broad (Fig.3d), being derived from the dominant slope in the NZLRI, most landslides occurred on slopes exceeding 20°. The slope angle distribution is similar to those from soft Tertiary lithologies. Landslides on Miocene andesite in the Kaimai Range (Jane and Green 1983) have a limiting slope of 15°, and mean slopes of 31 to 42°, depending on landform elevation.

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Appendix 1: Landslide surveys

Author	Site	Lithology	Vegetation	Survey type	Period covered (Date)	Area surveyed (ha)	Area eroded (%total)	Landslide scar N	Landslide scar Mean slope (°)	Landslide scar Range (°)	Landslide scar 95% slope (°)	Parent slope (°)
Blong (1974)	Mangawhara Valley	Weathered Mesozoic greywacke	Pasture	Profiles	1966-67	-	-	77	32.4	17-48	20	29.3
Blaschke (1988)	Waitiri-Kirai, Taranaki	Tertiary hard Sdst	Native forest	Plots	c.1880-1986	1	30	8	38.7	23-48	30	35.4
Crozier et al. (1980)	Pakaraka, Wairarapa	Tertiary Mst,Slst	Pasture	Point/scar	1977	23	9.7	110	c.33-34	24-53	28	31
DeRose et al. (1993)	Makahu, Taranaki	Tertiary hard Sdst	Pasture	Profiles	1905-90	80	21	30	33.3	21-49	28	32.2
DeRose (1994, 1995)	Makahu, Taranaki	Tertiary hard Sdst	Pasture	DEM'	1905-90	120	6.5	920	34.6	21-54	28	26.9
Eyles (1971)	Tangoio Reserve	Pleistocene Sst,Slst	Pasture	Profiles	1938-71	162	17	>210	32.4	21-49	24	24.4
Eyles et al. (1978)	Wellington City	Jurassic greywacke	Gorse-scrub	Grid/map, slope profile, air photo	1974 1976	- -	- -	30/1149 850	49	27-69	33	61
Harmsworth et al. (1987)	Otoi Catchment	Tertiary Mst,Slst,Sdst	Pasture	Transect	1985	161	2.2	205	c.36	18-61	24	-
Harvey (1975)	Port Hills, Canterbury	Loess/Basalt	Pasture	Point/scar	1975	-	0.02-1.2	519	c.38	26-60	c.28	20-40
In'T Veld and de Graaf (1990)	Emerald hills-Arai Te Matawai	Tertiary Mst,Sdst	Pasture	Transect	1988	232	4.3	547	27.4	8-62	18	-

Jane and Green (1983)	Kaimai Range	Miocene andesite	Native forest	Aerial dot grid	1943-74	-	0.1-10	>150	31,36,42	15->40	-	-
Laffan (1979)	Punakaiki-Charleston	Tertiary Sst Granite/gneiss /greywacke	Forest-clear fell	Air photo	-	7,850	0.1-5	>63	>30	13->30	-	-
Lawrence et al. (1982)	Eastbourne, Wellington	Loess/ Greywacke	Gorse-scrub	point/scar	1977 cut/fill natural cliff			 76 31 13	 55 44.5 49	 28-80 29-58 38-65	 33 36 41	 - - -
McConchie (1977, 1980)	Stokes Valley		Urban		1976	1270	0.3		>30	19-		
O'Loughlin and Pearce (1976)	Notown, West Coast	Tertiary hard Sdst, Stst	Clear fell	Point/scar	1965-75	550	<10	127	33	25-44	27	-
Page et al. (1994)	Tutira, Hawke's Bay	Tertiary Sst, Sdst	Pasture	Air photo dot grid	1988	3208	4	126	30.6	18-58	21	-
Pain (1968)	Hunua Range	Greywacke	Forest/ pasture					25 25	33.2 28.6			
Phillips (1988)	Waitahaia, East Cape	Cretaceous Sst, Sst/Mst	Pasture/ scrub/forest	Air photo point/scar.	1980-82	1670	0.5-1.6	116	35	-	21	-
Salter et al. (1981)	Thames-Te Aroha	Miocene andesite	Pasture/scrub /forest	Air photo	1981	81,000	-	7080	-	8->35	20	-
Selby (1976)	Hapuakohe Range	Weathered greywacke	Pasture	point/scar	1973	-	4.4	36	34	-	-	-

Sdst = sandstone, Sst = siltstone, Mst = mudstone, *DEM = digital elevation model

134

TREES FOR SURVIVAL - SO WHAT

Trees for Survival has grown from a 3 year trial project, involving 3 schools producing only 2000 plants per year, into a national programme with units in 40 schools growing at least 25,000 plants per year. In addition, although it still often involves Rotary and other service clubs, it is now a Charitable Trust, rather than a Rotary Programme.

Now that the project is no longer a "Rotary Project", placement of a unit in a school is not necessarily reliant on involvement of a Rotary Club. What is critical, is that there is a commitment by some group to provide ongoing support to the school - that group may be a Regional Council, Landcare Group, another Service Club etc. Such a group will meet the initial cost of placing a Plant Growing Unit in a school ($3,000), plus the ongoing costs of growing seedling ($2-300 per year), and show ongoing interest and support of the project.

The Trees for Survival Management Committee has been established to provide ongoing coordination and assistance to all those involved with the project. This includes a regular newsletter, a "Growing Plants Successfully" video, and provision of 'trouble shooting' advise for units.

REGIONAL COUNCIL'S BENEFIT

Because the aim of Trees for Survival is to plant trees for erosion control, rather than straight beautification or revegetation, Regional Councils and other agencies can benefit from support of the units, in getting trees planted for erosion control, at a minimum financial cost to the agency.

For example, in the Auckland Region, the Soil Conservator assists the schools involved with the programme to identify farms to plant on, helps coordinate the planting day, and provides advise on species selection, establishment methods, and other issues. This requires a commitment of time, but very little financial input.

In addition, the ARC have partially sponsored the placement of a unit in a school associated with a Landcare Group, with the allocation of the plants grown by the unit being the responsibility of the Landcare Group. This would also tie in well with Beachcare / Coastcare / any Care Group.

In the Bay of Plenty, Environment BOP River Engineers have placed a unit in the Galatea School, to grow