EROSION SOIL LOSS AND RECOVERY ON EASTERN NORTH ISLAND HILLCOUNTRY – IMPLICATIONS FOR NUTRIENT MANAGEMENT AND PASTURE PRODUCTIVITY

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Abstract

Landslide scars previously dated (1977, 1961, and 1941) and sampled by Lambert et al. (1984) for pasture production and topsoil characteristics were re-sampled. Pasture dry matter production and selected soil properties were re-measured on the same scars and uneroded control sites for two years, from 2007 to 2009. Results show that after a further 25 years of recovery, no significant increase in pasture production had occurred on the 1941 and 1961 slip scars. Average dry matter pasture production on eroded sites increased from 63% to 78% of pasture production levels on uneroded sites, but improvement was restricted to the youngest 1977 slip scars, where dry matter production increased from 20% to 80% of uneroded levels. Maximum pasture recovery occurred within about 20 years of landsliding and further recovery beyond 80% of uneroded level was unlikely.

The recovery of pasture production on slip scars follows similar recovery to soil physical (e.g. soil depth, particle density, bulk density) and chemical properties (e.g. total-C, total-N). Topsoil depths on eroded sites were roughly a third of topsoil depths on uneroded sites, indicating reduced profile available water capacity on eroded soils. We were unable to determine if total C would recover to uneroded levels because of the high variability in total C at eroded sites. However, given that uneroded soils were formed under native forest and that new soils are forming under pasture (over a shorter period of time), it is unlikely total C will recover to uneroded soil levels. This research verifies the conclusion of Lambert et al. (1984) that it is unlikely pasture production on slip scars will return to production levels on uneroded sites in human time scales. The sustainability of pastoral agriculture on steeper slopes in soft-rock hill country comes increasingly under threat as pasture production declines due to the cumulative effects of erosion.

The permanent loss in productivity on erosion scars, due mainly to changes in profile available water capacity, also has implications for fertiliser application rates in highly eroded hill country. It is suggested that rates of fertiliser application should be reduced on highly eroded slopes to match the expected lower productivity yields. Over-application of nutrients on highly erodible land can lead to increased runoff of nutrients to water bodies.

Keywords: landslide erosion; pasture production; dry matter; carbon; soil recovery; soil nutrients; aerial topdressing; nutrient runoff

INTRODUCTION

Information on production losses due to soil erosion are essential for quantifying the biophysical and economic impacts of mass movement erosion, and to assess the sustainability of land use in New Zealand hill country. Soil slip erosion results in immediate and often dramatic reductions in pasture production on steep hill country (Lambert et al. 1984). Reductions in pasture production occur directly through the loss of topsoil as a consequence of erosion, and indirectly through reduced pasture yields on eroded ground (Blaschke et al. 1992). Quantification of economic and biophysical losses associated with soil slip erosion is crucial to justify the need for soil conservation and erosion control activities on steep hill country underlain by weakly consolidated lithologies, through implementation of farm plans.

In New Zealand, a national programme of research was conducted in the 1980s to assess the impact of landslide erosion on pasture production within North Island Hill Country (Trustrum et al. 1983). The research was undertaken at three sites with contrasting parent materials and climate, in Wairarapa (Lambert et al. 1984), Wairoa (Douglas et al. 1986) and Taranaki (DeRose et al. 1995). The first New Zealand trial was conducted from 1979 to 1982 on seasonally dry Wairarapa hill country (Lambert et al. 1984). The findings from this study were that pasture dry matter yields on young slip scars were ~20% of the yields produced on uneroded ground, and while such scars revegetated rapidly over the first 20 years and could attain 70–80% of original production, further recovery was slow, and complete recovery might never occur. As a result of the cumulative impact of repeated landslide events, permanent loss in potential pasture production of 2% per decade over whole hillslopes was predicted (Trustrum et al. 1983). Similar reductions in pasture dry matter production on slip scars were found in Wairoa (Douglas et al. 1986) and Taranaki (DeRose et al. 1995) hill country.

Much of the loss in pasture production was attributed to the slow recovery of topsoil, physical and chemical characteristics on the landslide scars (Lambert et al. 1984; Douglas et al. 1986), and reduced water holding capacities of shallower topsoils (DeRose et al. 1995). Lambert et al. (1984) and Sparling et al. (2003) estimated that recovery of topsoil characteristics on landslide scars in Wairarapa hill country would reach 80% of uneroded sites, over a timescale of 18–80 years. Total carbon (C), nitrogen (N) and phosphorus (P) increased with slip scar age in the first Wairarapa trial (Lambert et al. 1984), though no such trend was reported for Taranaki and Wairoa slip scars. There were no clear trends along the Wairarapa chronosequence in total P, or Olsen P in 2001 (Sparling et al. 2003).

To validate the previous findings of Lambert et al. (1984) and determine whether pasture dry matter production had further improved over the last 25 years, a new study modelled on the original Wairarapa trial was conducted from May 2007 to August 2009 on the original study site at Te Whanga. Progress of the study was reported in Rosser and Ross (2008, 2009).

METHODOLOGY

Study site

The trial site was located on permanent pastures at Te Whanga Station, Wairarapa, New Zealand (41° 1.9565S, 175° 44.530E). The terrain is steeply dissected by streams and is underlain by unconsolidated, tectonically deformed Tertiary siltstone. Hillslopes are in the range 25–35°. The study area comprises a small valley about 30 ha in area, and includes slopes of northwest (sunny) and southeast (shady) slope aspect. Soils at Te Whanga station are Taihape steepland soils (previously mapped as Kourarau series). Topsoils were recorded as thin (0.15 m) and subsoils often had alternating layers of subsoil and topsoil, or mixed homogeneous material without horizonation.

Deforestation of indigenous forest and conversion to pasture from 1860-1890 increased the vulnerability of steeper slopes to soil slip erosion (Trustrum et al. 1990). Extensive areas of soil slipping are a feature of this landscape, and hillslopes have a complex pattern of different-aged soil slip erosion scars (Fig. 1). Slips have occurred over many parts of the landscape, but typically occur on gully sides and contour concave slopes, leaving arcuate, tear-shaped scars around 50 m^2 in area (Vincent & Milne 1990). Landslides typically remove the upper 50–60 cm of the soil profile, exposing the subsoil (Sparling et al. 2003). The exposed subsoils have higher bulk densities, higher clay contents, and lower organic matter content compared with uneroded topsoils (Vincent & Milne 1990). The average depth of soil overlying bedrock was 0.45 and 1 m for eroded and uneroded sites, respectively (Lambert et al. 1984).

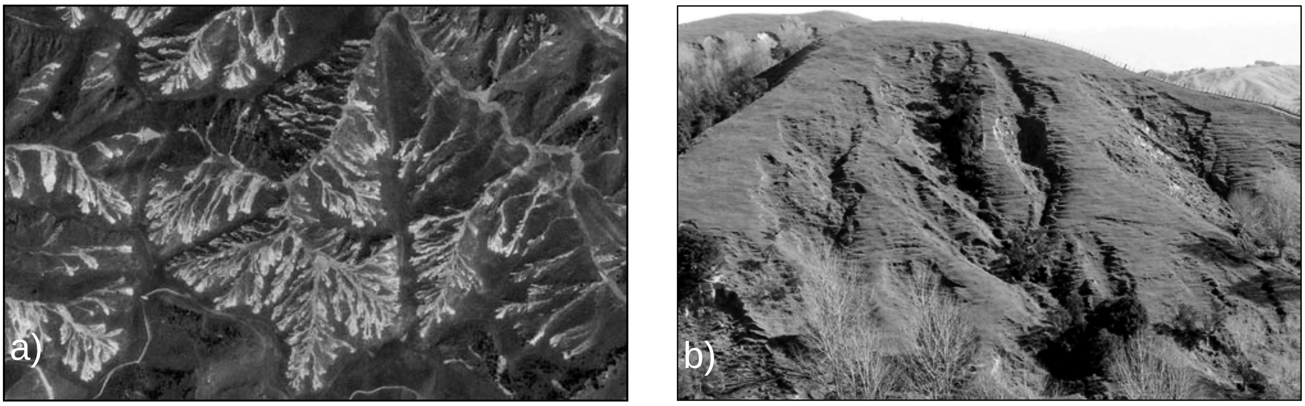

Figure 1. Extensive areas of soil slipping are a feature of this landscape, and hillslopes have a complex pattern of different-aged soil slip erosion scars. a) Soil slipping as a result of a storm in 1977 illustrates the scale of soil slip erosion at the study site. b) The south-facing (shady) hillslope in the study catchment.

Land Use Capability Classes are VI and VII, with moderate to severe erosion limitations to pastoral use. Average annual rainfall is ~ 1075 mm, and mean annual temperature ranges from 18°C in January to 7.5°C in July. Climate is overall seasonally dry, with frequently occurring summer droughts.

Measurement of pasture dry matter production

Sampling in 1979–1982: Trustrum and Stephens (1981) assigned ages to the landslip scars on hillslopes from archived aerial photographs. Storm-initiated landslip scars were dated as pre-1941, 1941, 1961, and 1977. In the original trial, Lambert et al. (1984) selected 40 measurement sites on these scar ages, as well as 5 sites on uneroded ground. Slopes at the measurement sites ranged from 27^o to 33°, and sites were split between slopes with shady and sunny slope aspects.

Sites were monitored for dry matter pasture production from August 1979 to August 1982. Dry matter pasture production was estimated using one 0.5 m^2 stock-exclusion cage per site. Grass was collected every 4–10 weeks, depending on the growth rate, by trimming with hand shears.. The cages were shifted to new nearby locations after each sampling.

Sampling in 2007–2009: The landslide scars known to have been initiated during storms in 1941, 1961, and 1977 were re-located. We were unable to re-locate any pre-1941 slip scars that had not re-activated. For each of these three landslide events we selected two representative scars. Pasture dry matter production was measured at each of the six sites using two 0.5-m^2 stock-exclusion cages located within the scar itself, and two cages placed on adjacent uneroded ground (control) with similar slope and slope aspect, giving a total of 24 cages. The locations of the sites are shown in Figure 2.

The trial was conducted from June 2007 to August 2009. Pasture was harvested with electric hand shears at intervals of 6–8 weeks during winter and 3–4 weeks during summer. The cages were shifted to new nearby locations after each sampling. Pasture botanical composition was visually estimated in December 2007, and the percentage of grass, clover, and weeds were estimated. A tipping bucket rain gauge was also installed on the site.

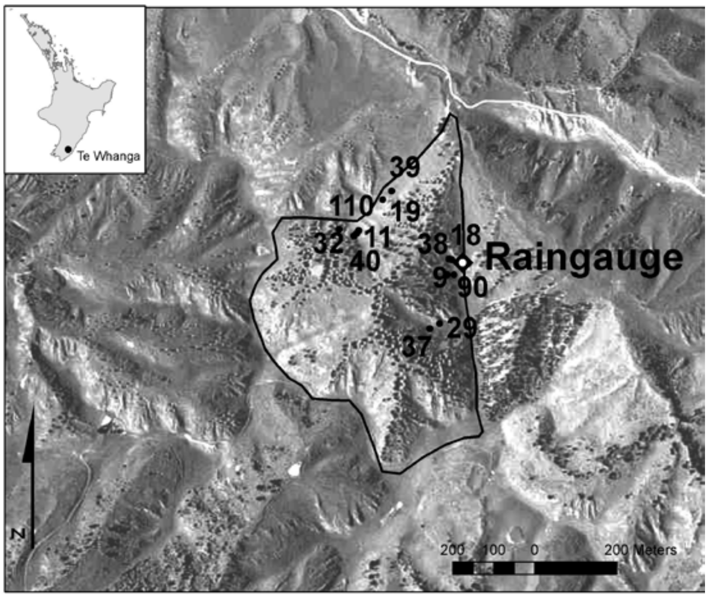

Figure 2. Location of pasture dry matter production monitoring sites within the study catchment at Te Whanga Station. The drainage basin of the study catchment is delineated, and the location of the rain gauge shown. The monitoring site numbers are also shown.

Soil sampling and chemical analysis

In the original pasture production trial, Lambert et al. (1984) sampled topsoils for laboratory characterisation. The exact same sites (erosion scars and uneroded sites) were subsequently re-visited at different times over the last 25 years by numerous researchers investigating additional aspects of the chronosequence (Table 1). Details of soil sampling and statistical analysis methods are given in Rosser and Ross (2011).

Table 1. Chronology of sampling at Te Whanga

Date	Reported by	Measurements
1981	Trustrum & Stephens 1981	Landslip scars mapped and their ages determined
1979–82	Lambert et al 1984	Pasture productivity monitored at 40 sites 7 sites sampled for full soil laboratory characterisation Analysed for total N, organic C, organic P, inorganic P, and Olsen P Topsoil depths measured
1984	National Soils Database	Soil profiles at 6 sites sampled for soil chemical and physical characterisation Analysed for total N, organic C, organic P, inorganic P, and Olsen P
1987	Sparling et al 2003	Sampled in 1987 by A West (Soil Bureau). Surface soil samples taken from landslip scars, and analysed for soil chemical and biochemical characteristics (refer to Sparling et al. 2003 for details).
2001	Sparling et al 2003	Surface soil samples taken from landslip scars, and analysed for soil chemical and biochemical characteristics (refer to Sparling et al. 2003 for details)
2007–09	Rosser & Ross 2008, 2009, 2011	Pasture productivity monitored at 24 sites. Surface soil samples taken from landslip scars and uneroded control sites, and analysed for soil chemical characteristics: pH, total C, total N, Olsen P, exchangeable bases (Ca, Mg, K, Na), CEC, BS Topsoil depths measured (refer to Rosser & Ross 2011 for details)

RESULTS

Recovery of pasture dry matter production

Average annual pasture dry matter production results for the earlier and current trials are listed in Table 2, and shown in Figure 3. Standard deviations are high because of the variability of pasture production through the year.

On uneroded sites, average annual production was 8760 kg DM/ha for this trial compared with 9490 kg DM/ha for the earlier (1979–1982) trial. Although not statistically significant due to seasonal effects (see below), the results suggest a slight decrease in dry matter production between surveys. For uneroded sites, pasture dry matter production on shady sites was roughly twice that on sunny sites in summer and autumn, and a third greater on sunny sites than shady in winter.

Table 2. Summary of average annual pasture dry matter production on erosion scars and adjacent uneroded sites

Trial	Slip year	Slip age (yrs)	Annual dry matter production (kg DM/ha)				
			mean	std dev	n	std error	% uneroded
1979–82	1977	3	2191	2661	105	384	23
	1961	19	7392	5895	105	840	77
	1941	39	6753	5649	126	749	72
	Pre-1941	74	6844	5912	105	803	73
	Uneroded	120	9436	7300	105	1041	100
	1979–82 average		6497	6169	546	256	63
2007–09	1977	31	6808	6120	60	1132	79
	1961	47	7009	6652	60	1205	83
	1941	67	6406	5933	60	1095	72
	Uneroded	148	8779	8372	180	876	100
	2007–09 average		7738	7486	360	402	76
	Overall average		6972	6745	906	219	

On eroded sites, average annual production was 6716 kg DM/ha for this trial compared with 5803 kg DM/ha for the earlier (1979–1982) trial (SED = 537 kg DM/ha/yr, n = 621) . Thus, the results suggest an increase in dry matter production between surveys for eroded sites. As a consequence, dry matter production on landslides scars as a percentage of uneroded levels, has increased over the two survey periods from 63% to 76%. The latest survey did not include young (3-year-old) scars, and this probably accounts for most of the increase in relative production on scars as a whole. In contrast to uneroded sites, on eroded sites there was no significant difference in production between sunny and shady sites.

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The results of the current trial indicate that no further improvement in dry matter production has occurred on the 1941 and 1961 scars (Fig. 3). Furthermore, there is no significant difference in DM production with scar age in this trial. The only scars that showed a significant improvement in production were the 1977 scars, where dry matter production increased from about 21 to 81% of uneroded levels. When growth data are combined from both surveys, it is clear there is no significant change in DM production for scars older than about 20 years in age (Fig. 4).

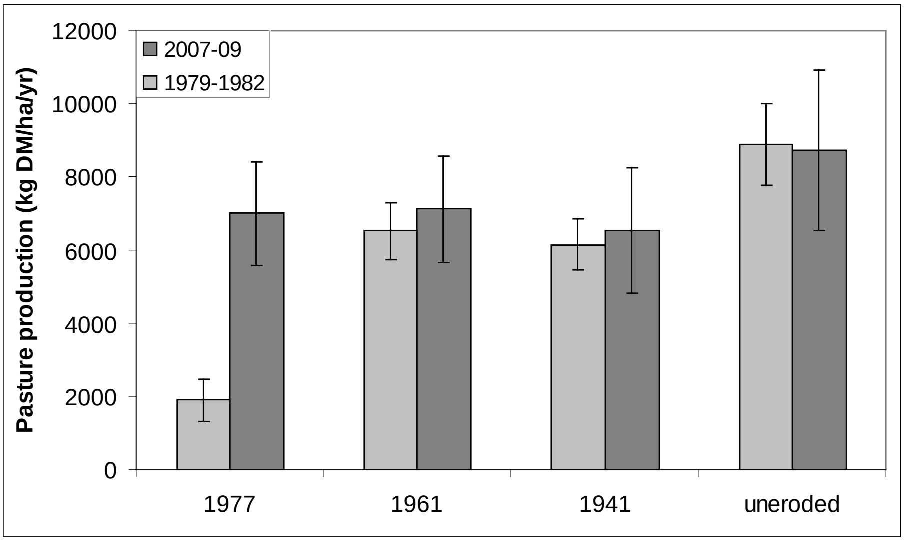

Figure 3. Comparison of dry matter pasture production on erosion scars between the two trials. The vertical bars are 95% confidence limits.

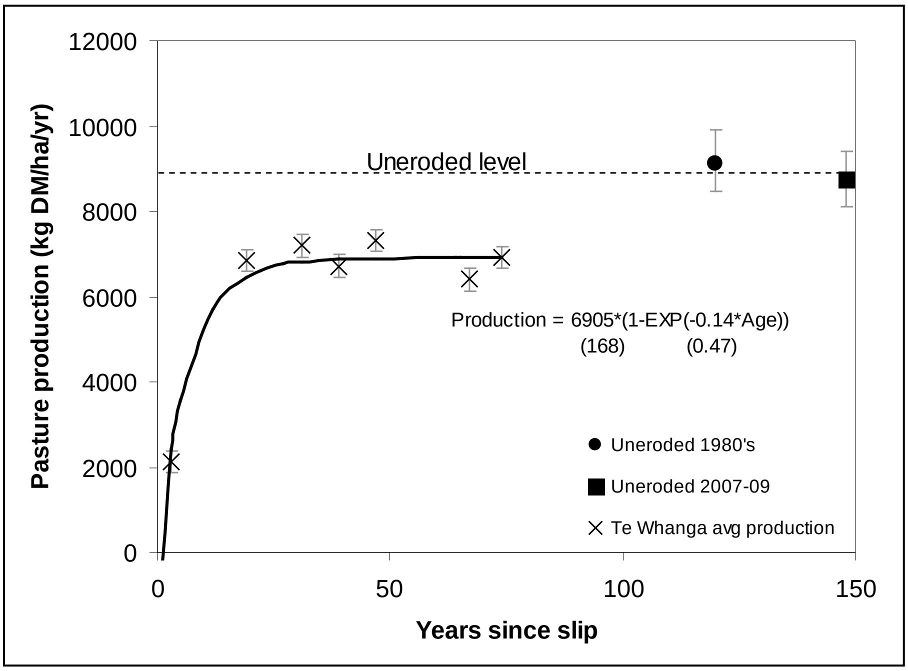

Figure 4 Pasture dry matter production recovery curve from the 66-year chronosequence of landslide scars (crosses) at Te Whanga Station using data from both trials. Each point represents the average production for each scar age. The uneroded sites were not used for curve fitting, and are shown for reference at the nominal ages assigned assuming deforestation and conversion to pasture in 1860. Vertical lines represent the standard error of the mean (n = 621), and values in brackets are the standard error of the parameter estimates. The relation accounts for 95.9% of the variance in pasture production (F.prob < 0.001).

Recovery of topsoil characteristics

Soil chemical properties that increased with time since slipping were C, N, and the ratio of C/N. Soil chemical properties that decreased with time since slipping were Mg, Na, and pH. There were no clear trends through time for exchangeable Ca and K, CEC, base saturation or Olsen P. There was a high degree of variability in the Olsen P values, and the range was from 6 to 48.3 mg/kg (very low to high), with both the highest and lowest values recorded at eroded sites. There was no difference between Olsen P on eroded sites between 1984 (mean = 16.9 ± 8.3 mg/kg, n = 7, SEM = 3.1) and 2007 (mean = 21.9 ± 7.8 mg/kg, n = 24, SEM = 1.6). There was also no difference in Olsen P between eroded (mean = 15.1 mg/kg ± 7.8, n = 28, SEM = 1.5) and uneroded sites (mean = 15.9 mg/kg ± 7.1, n = 18, SEM = 1.7). The high variability in Olsen P values probably reflect the uneven distribution of P- fertilisers from aerial topdressing, and the complex nature of soil properties in hill country pastures.

Total C and total N showed a marked increase with slip age. Total C increased from 0.21% in 1-year-old erosion scars to 4% in 66-year-old erosion scars (R^2 = 0.61). The average total C for uneroded sites was 5.4%. Total N also increased from 0.03% in 1-year-old erosion scars to an average of 0.34% in 66-year-old erosion scars (R^2 = 0.55). The ratio of C:N correspondingly increased from 6 to 12 over the 66-year period. Total N and C:N ratio were 0.4% and 11.8 respectively on uneroded sites. The C:N ratio showed a rapid recovery, reaching 90% of the uneroded values within 11 years of slipping. Sparling et al. (2003) reported an even faster rate of recovery for the C:N ratio; recovering to 90% within 5 years, and reaching maximum recovery of 92% of uneroded values after 59 years. Soil pH of the youngest erosion scars was high to very high: 6.8 and 8.2 from scars formed in 1981 and 1986 respectively, reflecting the calcareous nature of the parent material. Soil pH decreased with scar age to around 5.5, about the same pH of uneroded sites, as a result of leaching and the build-up of acidifying organic matter.

Results of the curve fitting to total C data (Fig. 5) indicate that the goodness of fit was not improved by employing an asymptote at a lower level than the uneroded sites. Although there appears to be quite a difference between the curves, there is no evidence to suggest one curve fits better than the other does (P-value = 0.5653). This infers that total C in topsoils on eroded sites is still recovering, and has not yet reached a maximum value. It also implies that total C in topsoils may reach uneroded values, but not for hundreds of years.

In 2007, total C on 66-year-old landslips had reached 76% of the uneroded values. Sparling et al. (2003) reported that soil C on 23- and 37-year-old landslide scars recovered to ~ 50% and 72% respectively, compared with soils from adjacent uneroded sites. After 60+ years of recovery, soil pH and C:N ratio had recovered to uneroded values, within the error limits. However, most of the characteristics indicative of soil nutrient status (C, N, P, Mg, K, Na, BS) had recovered to just 75–80% of the uneroded values. There were no clear trends through time for exchangeable Ca and K, CEC or Olsen P.

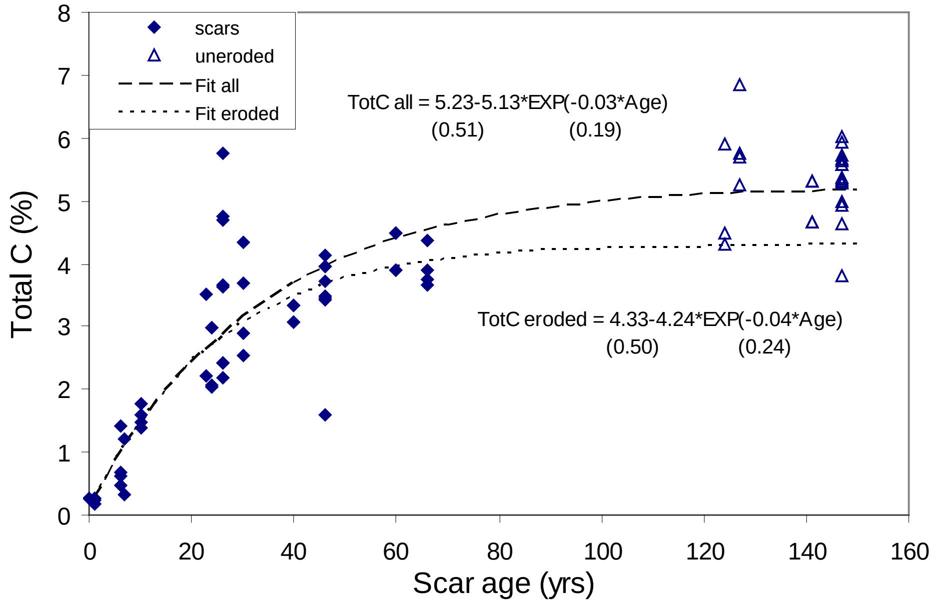

Figure 5. Results of curve fitting to total C. The upper curve shows a single line fitted to sites of all ages (eroded + uneroded) (P-value = 0.50), and the lower curve is fitted to the slipped sites, unconstrained by the uneroded sites (P-value = 0.56). Values in brackets are the SE of the parameter estimates. Uneroded sites are plotted at the nominal ages assuming deforestation and conversion to pasture in 1860.

Topsoil depth: In 2009, the average topsoil depth was 5.9 ± 3.4 cm (n=320) on landslide scars and 16.3 ± 4.5 cm (n=320) on uneroded sites. Depth to bedrock was 45 cm at scar sites and 98 cm at uneroded sites (in the 1980s). Most landslides were initiated at the interface between the subsoil and siltstone (Vincent & Milne 1990). Much of the subsoil remained through displacement downslope, mixed with some topsoil. Typically, about 50 cm of subsoil remained at most scar sites (Vincent & Milne 1990). Field observations suggest the entire soil profile to the siltstone bedrock was only generally removed at the head of slips. Unexpectedly, there was no real trend between topsoil depth and scar age (R^2 = 0.0015), which may be a reflection of the very narrow range of topsoil depths on eroded sites (3.3–8.4 mm). As mean slope increased, topsoil depths decreased, reflecting the increasing incidence of landsliding with increasing slope (Trustrum et al. 1990). However, within eroded and uneroded classes there was no relationship between topsoil depth and slope.

Relationship between pasture production and soil characteristics

Pasture dry matter production on eroded sites is related to the recovery of topsoil characteristics. While there were significant differences in topsoil depths and bulk density between eroded and uneroded sites, and weak trends of increasing production with decreasing bulk density and increasing topsoil depth (Fig. 6), due to high variability and small sample sizes, no statistically significant trends were identified between pasture production and topsoil depth (F.prob = 0.500) or bulk density (F.prob = 0.216) at eroded sites. No significant interaction was indicated between pasture production and depth to siltstone.

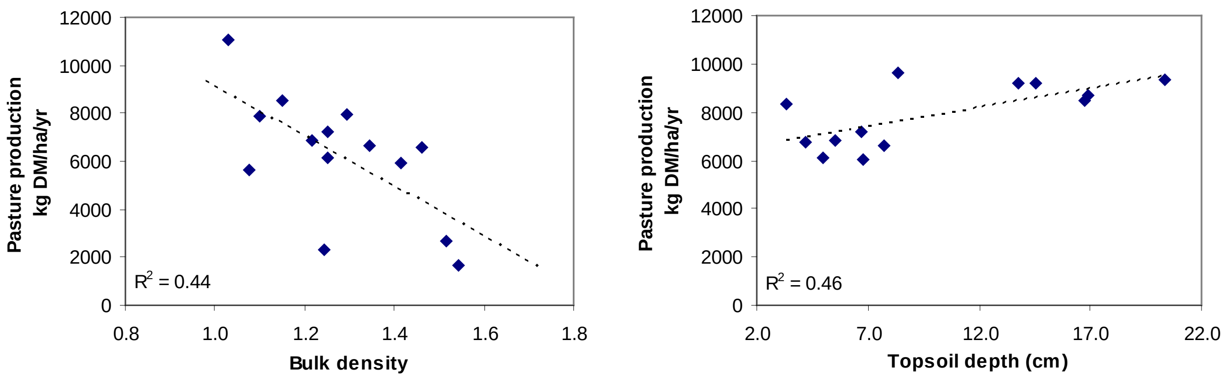

Figure 6. Interaction of pasture dry matter production with bulk density and topsoil depth for all sites.

We evaluated the relationship between pasture production and soil C and N because of their influence on soil physical properties (through organic matter) and nutrient status, respectively. Significant relationships between soil chemical characteristics and average pasture dry matter production were observed for Total C and Total N. Total C was the only highly significant interaction (F.prob <0.001), but strong relationships were also apparent with Total N (F.prob = 0.002), and Na (F.prob = 0.011). There was a weak trend of increasing pasture production with increasing Olsen P (Fig. 11); however, this relationship was not statistically significant (F.prob = 0.451). The notable absence of a relationship between Olsen P and pasture dry matter production in our data is most likely a reflection of the high variability of Olsen P values (6–48.3 mg/kg). Soil characteristics on newly exposed landslide scars were generally very similar to those on the non-slipped sites at 50–60 cm depth (Sparling et al. 2003).

DISCUSSION

Pasture recovery

In the first study on the recovery of pasture production and topsoil characteristics following landsliding, Lambert et al. (1984) found that young slip scars were producing ~20% the pasture dry matter yields of uneroded ground and that scars revegetated rapidly over the first 20 years, reaching 70–80% of original production (Fig. 4 and Table 2). But further recovery was slow and they concluded that complete recovery might not occur in human life times. Our research confirmed the Lambert et al.'s (1984) conclusion, with the oldest (1941 and 1961) slip scars showing no significant improvement in pasture production after a further 25 years. Pasture dry matter production on the 1977 scars (which were 3-years old in the original survey) increased from an average of 20% to 80% of uneroded levels between the two trials, further confirming results of the earlier study.

Although there were significant differences between pasture dry matter production on eroded and uneroded sites, in contrast to the results of the first trial, no significant relationship was found between pasture production and slip age in this trial. The most likely explanation is that all scars in our trial were greater than 20 years old, whereas 3-year-old scars were included in the earlier trial and these had minimal pasture growth rates, averaging just 7 kg DM/ha/day. Regression of slip age versus pasture production revealed that the recovery of slip scars reached a maximum at about 20 years, and beyond that further recovery was very slow.

Furthermore, a wider scar age range was studied in the earlier trial, with slip ages ranging from 3 to 74 years, whereas the age range of slips in the latter trial was 27–67 years.

Recovery of topsoil characteristics

The recovery of pasture production was linked to the recovery of topsoil physical and chemical properties of eroded soils by Lambert et al. (1984), who concluded that reduced pasture production on erosion scars was most likely due to the dense, clay-rich substrates, with high bulk densities, that were exposed by erosion. Sparling et al. (2003) reported that bulk density and particle density on the same slip scars decreased with slip age, although they did not find any corresponding trend through time for porosity or available water for individual soil samples. Preliminary analysis of unpublished neutron probe data (K. Vincent, pers. comm.) collected from 1981 to 1983 from the same sites at Te Whanga had shown that more water could be extracted from uneroded sites. A more thorough analysis of the dataset is required to confirm and validate these findings, and to relate it to pasture production; however, it is likely that reduced profile available water capacity is a limiting factor for plant growth on eroded landslide scars (DeRose et al. 1995).

Lambert et al. (1984) and Sparling et al. (2003) estimated that recovery of topsoil chemical characteristics on landslide scars in Wairarapa hill country would reach 80% of uneroded sites, over a timescale of 18–80 years. Sparling et al. (2003) showed that biochemical characteristics recovered at a much faster rate than chemical or physical characteristics. Our data confirm these earlier findings: after 60+ years of recovery, soil pH and C:N ratio had, within the error limits, recovered to uneroded values. However, most of the characteristics indicative of soil nutrient status (C, N, Mg, Na, BS) had recovered to just 75–80% of the uneroded values, and it is these components, coupled with reduced water holding capacity, that are ultimately limiting recovery in pasture growth at eroded sites. to ,

Although total C on uneroded sites was significantly greater than on eroded sites, there was no evidence in our data to suggest that recovery of total C on erosion scars had reached a maximum (i.e. further recovery can be expected) or that recovery was restricted in the long term to having a value less than uneroded sites. As the original soils were formed under forest, with inputs of organic matter over a very long period (hundreds to thousands of years) followed by about 150 years of pasture inputs, and taking into account carbon turnover rates and levels of inert soil carbon reported by Tate et al. (1995), the new soils being formed under pasture are unlikely to reach uneroded levels of soil C within a few decades.. Soil C stocks on eroded sites are likely to remain diminished compared with uneroded levels because of diminished topsoil and subsoil depths, and differences in organic matter compositions found under pasture and forest (Beets et al. 2002). The original uneroded soils were formed under forest, and typically included a? build-up of litter and humus in the topsoil.

Total C recovered at a similar rate, but to a higher level than modelled by Lambert et al. (1984). If the model describing soil C recovery through time on slip scars is unconstrained by soil C levels at uneroded sites, our data indicate recovery of C to 74% of uneroded levels within about 60 years. Lambert et al. (1984) predicted soil C recovery to 60% of uneroded levels within about 40 yrs, but no further recovery was expected. Data in Sparling et al. (2003) also indicate recovery of C to about 76%. Addition of this new data has shown that soil C levels have increased slightly since the 1980s, but are unlikely to attain soil C levels on uneroded sites for a very long time.

Influence of soil properties on pasture production

Pasture dry matter production on slip scars increased in proportion to improvements in soil chemical and physical properties associated with soil formation processes on the bare slip scars. Improved pasture production was correlated with the build up of soil C, N and other indicators of soil nutrient status (K, Na etc) and physical properties. Although interactions between pasture production and topsoil depth and bulk density at eroded sites were statistically weak (due to the variability and small sample numbers), the relationships between topsoil depth and bulk density with production were evident when both eroded and uneroded sites were compared. This suggests that soil physical properties, through their influence on profile available water, are also limiting factors for plant growth on erosion scars.

Lambert et al. (1984) attributed the lower pasture productivity on younger erosion scars to the physical properties of eroded soils, rather than to soil chemical factors. They concluded that reduced pasture production on erosion scars was most likely due to the dense, clay-rich substrates with high bulk densities that were exposed by erosion. Soil physical characteristics were not remeasured in this study (2007-2009); however, Sparling et al. (2003) reported that bulk density and particle density decreased with slip age.

Moir et al. (2000) identified soil moisture, climate, and soil fertility as the three major factors influencing annual pasture production in a modelling exercise using field trial data from nearby Wairarapa hill country farms (at Whareama, Gladstone and Mauriceville); however, Moir et al. (2000) did not include eroded sites in their study. Our data suggest that erosion, through the loss of soil, particularly topsoil, directly affects the soil moisture-holding capacity, through reduced topsoil and subsoil thicknesses and organic matter content, which also affect the soil nutrient status. Soil erosion is thus another important factor influencing annual pasture production in New Zealand hill country.

Implications

These research results have implications for the long-term sustainability of pastoral farming on steeper slopes underlain by poorly consolidated parent materials. In a survey of catchment condition at Te Whanga, Stephens et al. (1983) showed that the hillslope units studied in this project occur within landforms that represent 56% of the total area of Te Whanga station and Trustrum et al. (1983) determined that the overall loss in potential pasture production on these hillslopes was 18%. It is likely that this number has increased because of the cumulative effects of new landslide scars in the study area over the last 25 years. This has the potential to represent a significant loss in pasture production resulting from soil erosion for stations such as Te Whanga. The landslide scars are expected to heal with time but not to uneroded soil levels in human time scales.

The results from this study have shown that there is a permanent loss in productivity on erosion scars, and that on these highly eroded slopes nutrient levels are not the main drivers of pasture production. The slow recovery of soil physical properties that contribute to reduced profile available water-holding capacity, such as soil depth, bulk density, and organic matter content, are most likely preventing production levels from returning to those of adjacent uneroded sites. Steep hill slopes underlain by highly erodible lithologies are likely to have both a greater proportion of slopes occupied by erosion scars, and overall lower production levels, compared with uneroded slopes. Increasing nutrient application rates where grass growth is constrained by factors other than fertility may not lead to increased production gains (Gillingham 2001). Futhermore, aerial topdressing of fertiliser in hill country is usually applied as blanket rates across large blocks of land, based on average production values. To maximise production efficiency on highly eroded land, nutrient application rates should be targeted to match the reduced productive capacity. Over-application of nutrients on highly erodible land with lower expected production yields can lead to wastage and increased runoff of nutrients to water bodies. Reducing nutrient application rates to match reduced production yields on highly eroded land would result in the co-benefits of reduced cost ($) and reduced runoff of nutrients to streams.

Landsliding has the potential to cause significant losses of soil C from the landscape. Baisden et al. (2002) estimated the removal of 36–90 MgC/ha between 1984 and 2001 from Te Whanga Station alone. Soil erosion also has the potential to affect the spatial distribution of soil C stocks in the landscape, through the translocation and deposition of debris flow/colluvial material. It was estimated that 50% of sediment generated by shallow landslides in the Te Arai catchment, East Coast, remained on the hillslopes (Page et al. 1999). The fate of redistributed soil C through erosion remains unclear, and the mineralisation rate of exposed C in soil aggregates, and that of buried C, is the focus of this debate (Yadav & Malanson 2009). At present we do not know what the organic matter levels or soil C distribution are in the reworked and buried material, or how they are changing with time, and this is the focus of current research.

CONCLUSIONS

Topsoil properties and pasture dry matter production on landslide scars in the Wairarapa recovered to about 80% of uneroded levels after 66 years, verifying the conclusions of Lambert et al. (1984) that pasture recovery on landslide scars beyond 80% was unlikely. A gradual increase in production on older scars was also suggested by the exponential pasture recovery curves. Our study shows that no additional improvements in production occurred after a further 25 years of recovery on the oldest (1941 and 1961) slip scars at Te Whanga. Average dry matter pasture production on eroded sites increased from 63% to 78% of uneroded levels, but improvement was limited to the youngest slip scars initiated in 1977 (3 years old in the first trial). Maximum pasture recovery occurred within about 20 years, and beyond that there was no evidence of further recovery. The exponential form of the pasture recovery curve of Lambert et al. (1984) was also confirmed. It is unlikely that pasture production on slip scars will return to uneroded levels within human lifetimes.

The recovery of pasture dry matter production was accompanied by similar increases in soil C and N, which had reached 76% and 78%, respectively, of the uneroded values after 66 years. Our results support conclusions by other researchers (Lambert et al. 1984; Trustrum & DeRose 1988; Sparling et al. 2003) that some soil chemical characteristics (total C, N) may not recover to uneroded soil levels within human lifetimes. However, our data were inconclusive on whether surface total C would recover to values on uneroded sites in the long term. Other soil properties (C/N, pH, Mg, Na, and CEC) are expected to recover to uneroded values within human time scales and are not the cause of permanent reductions in pasture growth on older landslide scars.

The implication of this and previous research is that the sustainability of pastoral agriculture on steeper east coast hill country, particularly in areas underlain by poorly consolidated parent materials, will increasingly come under threat as pasture production declines as a consequence of the cumulative impacts of erosion. Furthermore, increasing the nutrient application rate on highly erodible land is unlikely to result in increased pasture production. Nutrient application rates should therefore be better aligned with lower anticipated production rates.

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