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Climatic and anthropogenic effects on soil transport rates and hillslope evolution

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Abstract Vegetation change, whether it be of anthropogenic or climatic origin, can have dramatic effects on landscape form, processes and sediment yield. General conceptual models for relationships between climate, vegetation and sediment yield exist for whole landscapes, but no rigorous analysis of the effects of vegetation change on sediment transport, in the absence of overland flow, has been done from soil-mantled hillslopes. Here we investigate the rate of erosion and sediment delivery from soil-mantled hillslopes underlain by loess, over long (27 ka) and historic (50 year) time scales. In a humid environment the change from grassland/shrubland to tall forest across the Pleistocene/Holocene boundary resulted in a 60% increase in sediment flux. We attribute this to increased soil disturbance and transport by tree-throw. In a presently subhumid landscape, average soil transport efficiency over the same 27 ka period, as quantified by the soil transport coefficient (the proportionality constant relating soil flux to hillslope gradient), was very similar to the humid area, despite a semi-arid or even drier phase prevailing during the Late Glacial in the subhumid region. This result suggests that any differences in soil fluxes and erosion rates during the Late Glacial, imbued by the very different climates in the two regions, have been overwhelmed by processes associated with the Holocene forest phase. The soil transport coefficient for the historical (last 50-year) period at the subhumid site, quantified by ^{137}Cs analysis, indicates the present erosion rate under introduced grazed pasture is higher than the long-term averages at both sites, higher than that which occurs under native tussock grasslands and comparable to rates under forest. We propose a general scheme to describe the relationship between climate/vegetation and sediment yield on soil mantled hillslopes that have a trough form: the minimum coincides with subhumid grassland/shrubland, while sediment flux maxima may be associated with climatic extremes (humid forested landscapes and arid and hyperarid deserts).

Key words climate change; vegetation change; soil erosion; ^{137}Cs; hillslope evolution

INTRODUCTION

Vegetation has a profound influence on landscape processes and morphology (Dietrich & Perron, 2006). Consequently, climatically or human-induced changes in vegetation are often accompanied by major landscape responses. For example, in steeplands, loss of root cohesion following removal of forest results in an increased prevalence of shallow landslides (Montgomery *et al.*, 2000). Analytical and numerical models suggest the long-term effect of persistent decreased root reinforcement is to produce a landscape of lower relief with higher drainage density (Istanbulluoglu & Bras, 2005). On agricultural lands, removal of vegetation by cultivation or vegetation depletion by grazing animals often results in enhanced overland flow erosion due to decreased interception and infiltration of rainfall, and increased boundary shear stress on soil particles. Less clear is the influence of changes in vegetation on processes on soil-mantled hillslopes where slope-dependent (creep) processes dominate. Some studies (Carson & Kirkby, 1972; Young, 1972; Selby, 1974; Jahn, 1989; Malmon & Dunne, 1996) suggest that bare or sparsely vegetated soil on hillslopes experiences more rapid transport due to its greater exposure to dry ravel processes, rainsplash and expansion–contraction cycles, while others find evidence for increased soil transport due to dilation and tree throw under tall forest (Nash, 1980; Roering *et al.*, 2002, 2004). Assuming a simple linear slope-dependent transport model, a soil transport parameter (K – often called the diffusivity) relates soil flux, q_s to hillslope gradient, ∇z (equation (1)):

$$q_s = K\nabla z \qquad (1)$$

The studies cited above suggest a complex relationship between *K* and vegetation. The nature of the dependency is important for understanding and modelling of the effects of future climate and anthropogenically-induced vegetation changes on soil-mantled hillslopes. In this study we investigate the vegetation dependency of soil transport, and hence *K*, on soil-mantled hillslopes, over long time scales where vegetation change is related to glacial–interglacial climate change, or over short time scales where vegetation change is anthropogenic.

METHODS

At Charwell basin (Fig. 1) in north Canterbury, South Island, New Zealand (NZ), we quantify hillslope sediment flux rate from the rectilinear sideslopes of a gully formed in a rolling, dissected, loess-mantled alluvial terrace (Dillondale Terrace – Bull, 1991). The present climate is mild temperate, with a mean annual rainfall (MAR) of approx. 1200 mm. The site is now used for pastoral farming but was covered by beech forest at the time of land clearance in the 19th century. The hillslope sediment has been accumulating in the gully floor since approx. 50 ka (Hughes, 2008), and was drilled and sampled by hand auger. We quantify the rates of gully infilling in two phases: (1) an early LGM to Holocene transition phase (abbreviated LGIT – Last Glacial–Interglacial Transition); and (2) the Holocene phase. The base of the LGIT in the gully was established by high concentrations of volcanic glass shards at 2.7 m depth derived from the 27 095 cal. year BP Kawakawa Tephra (Lowe *et al.*, 2008). This tephra fell within the most recent period of cold climate and maximum ice extent recognised as the NZ LGM (Suggate & Almond, 2005; Newnham *et al.*, 2007). The upper boundary of the LGIT phase, and the base of the Holocene phase was established by a rapid change in relative abundances of grass type *vs* tree type phytoliths at 1 m depth.

Phytoliths are microscopic particles of plant opaline silica that have sufficiently characteristic morphologies to allow their affiliations to various taxonomic categories to be established. Distinguishing tree/shrub *vs* grass forms is straightforward. Pollen diagrams from South Island,

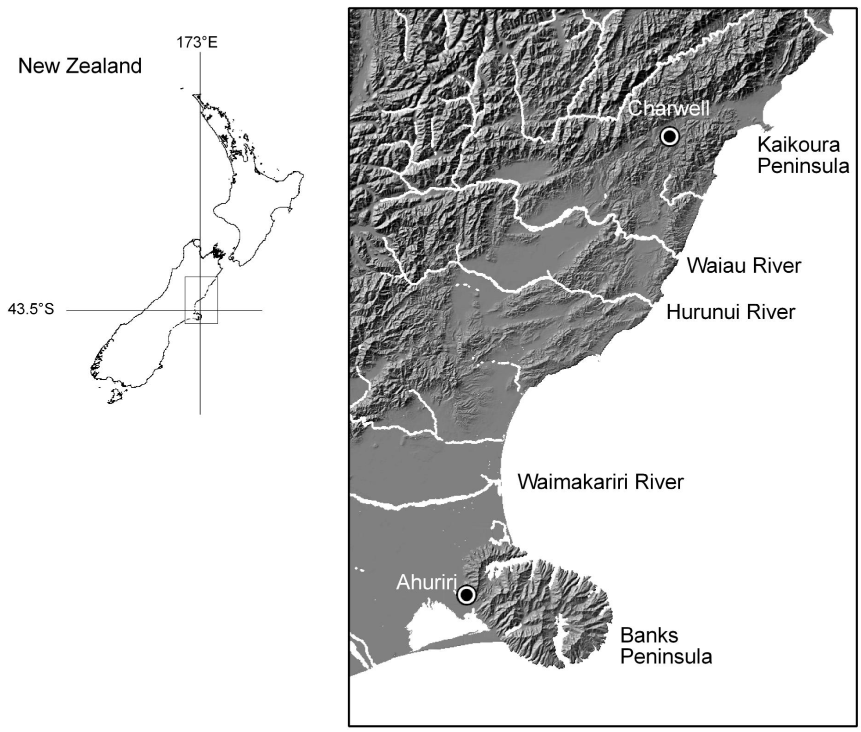

Fig. 1 Location of study sites.

NZ ubiquitously show a transition from grassland and shrubland in the Late Glacial to forest around the Holocene boundary. Near the Charwell basin study site, pollen evidence and radiocarbon dates from wood have constrained the grassland/shrubland to tall forest transition to 10, 690 ± 1690 cal. year BP. The upper boundary of the Holocene phase is the present day land surface (0 year). Volumes of sediment (expressed as m^3 of sediment per m length of contour) accumulated in each phase were calculated using the thickness of the two sediment packages, and the cross-sectional profile of the gully as delineated by additional drilling. The sediment volume in the LGIT phase had to have subtracted the volume of primary loess accumulated since Kawakawa Tephra in order to isolate the volume of transported soil. This was estimated using the loess mass flux calculated from the thickness and density of primary loess above Kawakawa Tephra on the uneroded terrace tread above the gully. The volumes of each phase were then scaled by the ratio of the average sediment bulk density to the bulk density of the hillslope soils to account for differential compaction, and to allow fluxes of hillslope sediment to be calculated. Flux rates were calculated for the two phases by dividing the cross-sectional volume of each gully deposit by the relevant length of time.

At Ahuriri Quarry (Fig. 1) on the western flank of Banks Peninsula in Central Canterbury, a convex hillslope has formed across a thickly (approx. 10 m) loess-mantled ridge, aligned in an east–west direction, underlain by eroded Miocene basalt. The climate is presently mild temperate and subhumid with a MAR of approx. 690 mm. Vegetation through much of the Holocene was probably podocarp-hardwood forest, but this had been replaced by native tussock grasses by 1830 (Wilson, 1992) and later by introduced pasture grasses. At this site we quantified erosion over two phases: the last 27 ka, again using the presence of Kawakawa Tephra in the loess, and the last 50 years using ^{137}Cs inventory. The soil transport coefficient, *K*, was used to quantify the efficacy of soil erosion. This parameter, by normalising for hillslope gradient, encapsulates the energy expenditure of soil disturbance processes (Roering *et al.*, 1999; Yoo *et al.*, 2005), while being independent of erosion rate at different points on a hillslope.

Combining equation (1) with the continuity equation yields:

$$\frac{\partial z}{\partial t} = E = K \cdot \nabla^2 z \tag{2}$$

where E is erosion rate, and $\nabla^2 z$ is the second derivative of the hillslope profile, or hillslope curvature. This equation shows that where linear slope-dependent transport dominates, erosion rate is proportional to hillslope curvature with the constant of proportionality equal to the soil transport coefficient, *K*.

To calculate *K* for the last 27 ka period the method of Roering *et al.* (2002) was adapted. Briefly, this involved examining the relationship between erosion rate and curvature on the hillslope. We augered five holes along a transect, originating at the interfluve and aligned orthogonally to the north-facing hillslope. Soil was sampled in order to locate the emplacement horizon of Kawakawa Tephra. We calculated differential erosion over the last 27 ka at each sample site on the transect as the difference between depth to Kawakawa Tephra measured at the interfluve and at the site of interest. We then plotted differential erosion rate *vs* differential curvature between the hillslope transect sites and the interfluve. Local hillslope plan and profile curvature were measured by means of high resolution GPS topographic survey over an approx. 20-m-wide swath aligned parallel to, and centred on the transect (Lutter, 2007). Curvature was determined as the second derivative of a second-order polynomial fitted to the elevation data by least squares regression. The transport coefficient, *K*, was estimated from the gradient of the line of best fit of the differential erosion rate *versus* differential curvature plot (equation (2)).

For the period of the last 50 years we calculated *K* using a similar analytical approach but used relative depletion of bomb fall-out ^{137}Cs to quantify soil erosion. The total ^{137}Cs inventory was measured by gamma spectroscopy from auger borings to 40 cm depth for the five sites along the hillslope transect plus an additional 16 sites (but only drilled to 30 cm depth) located on the same hillslope. High-resolution GPS topographic survey was done at all additional sites to quantify local hillslope curvature. Caesium-137-based erosion rate was estimated according to the profile distribution model (Walling & Quine, 1993; Morgan, 2005). This model assumes an exponential decrease in ^{137}Cs activity with increasing depth and requires a shape factor parameter, h_0, to describe the penetration of ^{137}Cs into the soil. To derive this parameter, ten 35-cm-deep core samples were taken from the interfluve (assumed to be uneroded), each sectioned into 5-cm increments and bulked by depth increment. Air dried, bulked samples were then submitted for ^{137}Cs activity analysis. The shape factor was derived from the shape of the curve describing increase of total aerial activity with increasing mass-depth (= soil mass per m^2). The soil transport coefficient (K) was determined as the slope of a plot of the calculated erosion rate expressed in myear^{-1} *vs* hillslope curvature (m^{-1}).

RESULTS AND DISCUSSION

Charwell basin

Gully infilling rates show a 60% increase from the LGIT to the Holocene (Table 1) coincident with an amelioration of climate and a change in vegetation from grass/shrubland to trees and shrubs. Roering *et al.* (2002) used depth to Kawakawa Tephra in soils on the adjacent hillslope of the same gully, and hillslope curvature, to give an estimate for K during the Holocene of 0.012 m^2 year^{-1}, assuming that all erosion took place over the last 9 ka when forest was re-established. Relaxing this assumption gives an average K value over the last 27 ka of 0.004 m^2 year^{-1} (Fig. 2). Under the constraint that erosion rate increased by 60% from the LGIT to Holocene, and taking into account the durations of these periods, implies K values of 0.003 ± 0.001 m^2 year^{-1} for the LGIT grass/shrubland and 0.005 ± 0.002 m^2 year^{-1} for the Holocene forest.

Table 1 Charwell gully characteristics and infilling rates.

	Holocene	Pleistocene
Volume[a] (m^3 m^{-1})	34 ± 8	32 ± 12
Period of infilling (years)	10 690 ±1690	16 407 ± 2647
Flux rate (m^3 m^{-1}year^{-1})	0.0032 ± 0.0007	0.0020 ± 0.0008

[a] normalised by ratio of the average bulk density of the phase of infilling to the bulk density of hillslope soil.

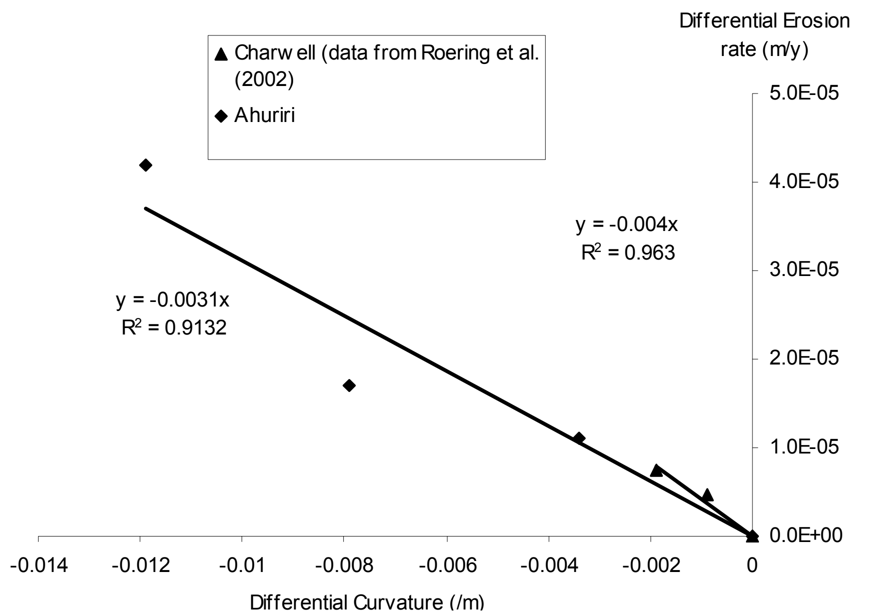

Fig. 2 Differential erosion rates over the last 27 ka *versus* differential hillslope curvature (with respect to the relevant interfluve site) along hillslope transects at Charwell basin and Ahuriri Quarry.

Roering *et al.* (2004) used a numerical simulation of soil and tephra grain transport along the same slope transect at Charwell basin, to estimate individual *K* values for the Holocene and LGIT of 0.016 m^2 $year^{-1}$ and 0.001 m^2 $year^{-1}$, respectively. Although the magnitudes of the *K* values are different, these different data sets point clearly to an increase in soil transport rates across the LGIT/Holocene boundary with the arrival of higher stature forest vegetation. We interpret our results in the same way as Roering *et al.* (2002, 2004), that the increasingly intense bioturbation regime under tall trees, which cause significant soil dilation and disruption after tree-throw, powers more vigorous downslope soil transport.

Ahuriri Quarry

At Ahuriri Quarry the data do not allow us to partition erosion into an LGIT and a Holocene phase. They do, however, allow us to make comparisons between the two study sites for the last 27 ka period, and to compare the historical (last approx. 50 years) soil transport efficiency under introduced pasture grasses with those under natural vegetation.

At the interfluve the Kawakawa Tephra emplacement horizon was recognised as the deepest major peak in glass concentration, which occurred at about 2 m depth. At the more convex hillslope sites the tephra datum was shallower. The plot of average erosion rate over the last 27 ka *vs* hillslope curvature at Ahuriri (Fig. 2) has a gradient (or *K* value) of 0.0031 ± 0.0004 m^2 $year^{-1}$, very similar to 0.0041 ± 0.0003 m^2 $year^{-1}$ at Charwell.

It appears that despite the differences in the present climate and the climate history of the two sites, the net effect of soil transport over the last 27 ka on these two hillslopes is very similar. Ahuriri is presently under a subhumid climate, but the presence of pedogenic carbonate in the loess, radiocarbon dated between 10 000 cal. year BP and 25 920 cal. year BP (Almond *et al.*, 2007), indicates a semi-arid climate during the LGM and LGIT. Phytolith evidence (P. Almond, unpublished data) shows that the vegetation during the phase of loess accumulation was tussock grassland similar to that of Charwell basin. This very dry climate might be expected to have reduced vegetation density and enhanced rainsplash-driven soil creep relative to Charwell basin, where, in contrast, evidence from diatoms in the gully infill confirms the LGM and LGIT as relatively wet periods there (Hughes, 2008). However, the generally conformable relations among sedimentary layers within the loess and the cross-cutting relation between the surface soil and sedimentary layers obvious in the quarry exposure suggest that most erosion occurred after the phase of loess accumulation, i.e. in the Holocene. These observations are consistent with an increase in soil flux rates with Holocene climate amelioration and recolonisation by forest.

The soil transport coefficient estimated for the last 50 years at Ahuriri Quarry, using ^{137}Cs inventory, is 0.007 ± 0.002 m^2 $year^{-1}$ (Fig. 3). Despite the relatively large uncertainty of *K*, which is related to the characteristically high spatial variability of ^{137}Cs activity, it appears that soil transport efficiency under the present grazed pasture is greater than the 27 ky-averaged rate at both Ahuriri Quarry and Charwell basin, and similar to or possibly even higher than the *K* value appropriate to Holocene forest quantified at Charwell.

These data suggest there is not likely to be any major increase in sediment flux from convex hillslopes, where creep-type processes dominate, after forest clearance and its replacement with pasture. But it seems the rate of transport may well be greater, at least under a subhumid climate, relative to native tussock grasslands. This may be due to grazing pressure and stock trampling, which reduce vegetation cover and expose the soil to rainsplash detachment.

Our results show a complex interaction between climate, vegetation, land management and soil transport on soil mantled hillslopes. Climatic factors of temperature and rainfall mediate vegetation change and, in so doing, affect the bioturbation regime and the extent of soil exposure. Climate also acts directly to influence soil transport by physical processes such as rainsplash and freeze-thaw. Langbein & Schumm (1958) reported a humped relationship between sediment yield from hillslopes affected by overland flow erosion and rainfall, with yield peaking in sparsely vegetated semi-arid landscapes affected by intense storms. Our results only deal with soil transport on hillslopes largely unaffected by overland flow erosion, but they suggest, for a given substrate, the relationship

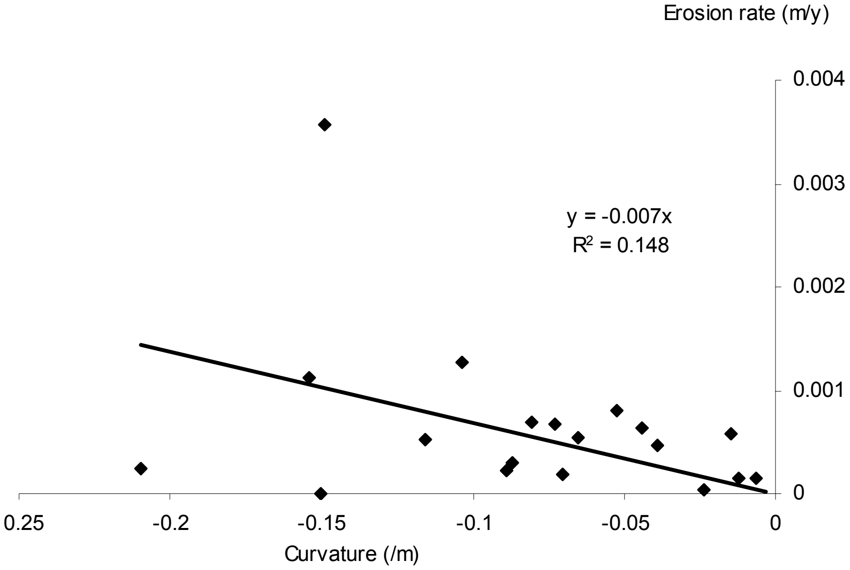

Fig. 3 Caesium-137-based erosion rates over the last 50 years at Ahuriri Quarry *vs* hillslope curvature.

between rainfall and soil transport by creep type processes may have the inverse form: at semi-arid to subhumid climates or cold climates where grasses and shrubs dominate, soil transport is minimised by low bioturbation and adequate ground cover, which ameliorates rainsplash detachment; at high rainfalls, where forest dominates, soil transport is maximised owing to intense tree-throw disturbance. Our results from grazed pasture suggest grazing pressure may enhance soil transport by rainsplash, but this effect will be highly sensitive to stock and pasture management, including stocking rate and rotation, stock type, and soil fertility. Whether very dry climates have higher or lower efficiency of soil transport is uncertain. In these landscapes the effects of rainsplash are minimised but other processes may act to disturb soil in the absence of any vegetation. Putkonen *et al.* (2008) conclude there has been no soil creep on hillslopes in the cold desert environment of the McMurdo Dry Valleys in Antarctica. In contrast, Dietrich & Perron (2006) document convex hillslopes in the Atacama Desert and on Mars, which they suggest are evidence of slope-dependent transport in the absence of vegetation. As yet, however, characteristic K values for the kinds of processes acting to disturb soil have not been quantified. Dietrich & Perron (2006) identify salt crystal growth as the mechanism of soil disruption in the Atacama Desert, but more research is needed in areas that are arid as opposed to hyperarid, which do not support accumulation of salts in soils and have minimal plant cover. Another dimension potentially missing from our study is the action of burrowing animals. New Zealand has no fossorial mammals, which are very effective in disturbing and transporting soils on hillslopes and which have very specific ecological affiliations (Yoo *et al.*, 2005). Mainland NZ did, however, probably have locally very high densities of burrowing sea birds prior to the arrival of humans and the mammalian predators they brought with them (Holdaway, 1999). Colonies of these birds can still be found on offshore islands and their burrowing density leads to soil disturbance at least as profound as that of fossorial mammals (McKechnie, 2006). We have no evidence that either of our sites was such a colony. Similarly, ecological change can bring about major shifts in burrowing invertebrates. In the Palouse region of eastern Washington State, USA, cold dry glacial phases induced a vegetation shift from grassland to Artemesia shrubland, and with it invasions of cicada (O'Geen &Busacca, 2001), which fed on the roots. The intensive burrowing of these animals may well have stimulated soil transport on hillslopes for reasons not encapsulated in the framework we present. On the basis of our results, acknowledging the limitations discussed above, we propose a "trough" or "monoclinal" relationship between soil transport efficiency, and vegetation and climate (Fig. 4) on soil-mantled hillslopes where creep-type processes dominate. We present this as a general rather than universal framework because of the potential for highly specific ecological responses to climate and vegetation changes in different landscapes.

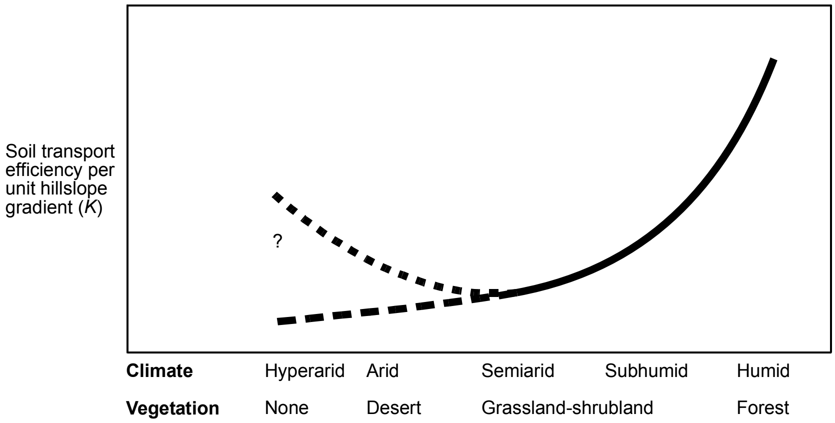

Fig. 4 The relationship between *K* and climate and vegetation.

CONCLUSIONS

In a humid region of eastern South Island, the efficiency of soil transport on loess-mantled hillslopes, where slope-dependent (creep-type) processes dominate, increased by 60% from the Last Glacial to the Holocene, coincident with the vegetation transition from grassland/shrubland to tall forest. This most likely resulted from a more intense bioturbation regime (tree wind throw). At a subhumid site with a similar loess substrate, the long-term (27 ky) average soil transport efficiency was similar to that of the humid region, despite a late Last Glacial arid phase in the subhumid region. It appears that this dry phase did not significantly increase or decrease soil transport efficiency to the extent of overwhelming the Holocene soil transport response. Data from both regions indicate that Holocene hillslope processes dominate hillslope response and sediment yield. The historical soil transport efficiency at the subhumid site, quantified by bomb fallout ^{137}Cs, under the modern grazed pasture was greater than the local long-term average, and possibly even greater than that under forest. Greater soil flux rates under introduced pasture grasses relative to native tussock grasslands may well be the direct effect of stock reducing vegetation density. We propose a general relationship between soil transport efficiency and vegetation/climate that has a trough form with the minimum coinciding with semi-arid to subhumid grassland or shrubland. The increases left and right of the trough correspond with enhanced soil transport under vegetation-free soils disturbed by physical pedogenic processes, and with enhanced tree throw under tall forest, respectively. Our conceptual framework does not account for fossorial animals.

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