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Shallow landsliding and catchment connectivity within the Houpoto Forest, New Zealand

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Abstract

Active landslides and their contribution to catchment connectivity have been investigated within the Houpoto Forest, North Island, New Zealand. The aim was to quantify the proportion of buffered versus coupled landslides and explore how specific physical conditions influenced differences in landslide connectivity. Landsliding and land use changes between 2007 and 2010 were identified and mapped from aerial photography, and the preliminary analyses and interpretations of these data are presented here. The data indicate that forest harvesting made some slopes more susceptible to failure, and consequently many landslides were triggered during subsequent heavy rainfall events. Failures were particularly widespread during two high magnitude (> 200 mm/day) rainfall events, as recorded in 2010 imagery. Connectivity was analysed by quantifying the relative areal extents of coupled and buffered landslides identified in the different images. Approximately 10 % of the landslides were identified as being coupled to the local stream network, and thus directly contributing to the sediment budget. Following liberation of landslides during high-magnitude events, low-magnitude events are thought to be capable of transferring more of this sediment to the channel. Subsequent re-planting of the slopes appears to have helped recovery by increasing the thresholds for failure, thus reducing the number of landslides during subsequent high-magnitude rainfall events. Associated with this is a reduction in slope-channel connectivity. These preliminary results highlight how site specific preconditioning, preparatory and triggering factors contribute to landslide distribution and connectivity, in addition to how efficient re-afforestation improves the rate of slope recovery.

Key words: landslide, slope-channel coupling, rainfall, vegetation, slope angle

Introduction

The level of connectivity within a catchment represents the strength of sediment coupling between the slope and channel domain. The influence of sediment transport within a catchment can then condition aspects of hydrology, ecology and geomorphology. Bracken and Croke (2007) separate catchment connectivity into three domains: landscape, hydrological and sedimentological. Vonnote *et al.* (1980) joined these domains together through the continuum theory which emphasises longitudinal, lateral, vertical, and temporal linkages throughout a catchment. Linkages in geomorphology are connected through the movement of sediment. Fryirs *et al.* (2007) apply the analogy of a "sediment conveyor belt" to describe sediment movement along a chain or the "sediment cascade" from the slope domain into the channel domain. The slope domain encompasses the landscape and sedimentological domains, whereas the channel domain is controlled by the sedimentological and hydrological domains (Bracken & Croke, 2007). However, sediment is seldom moved continuously or uniformly across the landscape. Fryirs (2012) explains how buffers, barriers and blankets impede sediment movement and transfer of sediment, describing sediment transfer along a "jerky conveyor belt". This spatial and temporal variability can make quantifying the "sediment budget" of a catchment difficult (Marutani *et al.* 1999). Catchment connectivity is facilitated or hindered by a range of intrinsic factors such as structural geology, lithology, topography, or scale, and extrinsic factors such as climate. The interaction of these factors defines the stability of the system and the thresholds for geomorphic change (Schumm, 1979). These regional factors can strengthen or weaken intrinsic and extrinsic geomorphological thresholds. The influence of several important regional factors relevant to this study are briefly described below:

Material properties and topography: Lithology, soil cover characteristics and the topography of a catchment precondition a slope to erosion and sediment supply. Phillips *et al*. (2007) link weakly lithofied units to high sediment budgets in the East Coast Region, New Zealand; however, within the Houpoto site, where shallow landsliding is the dominant type of mass movement, the main preconditioning factor for landslides is probably more directly related to the build-up of regolith from the bedrock rather than the direct influence of the bedrock strength. Larger sediment budgets provide extra material for conveyance and facilitate connectivity (Church, 2002). Steeper topographies encourage the coupling of sediment from the slope domain to channel domain. However, some literature suggests that the steepest gradients in a landscape do not necessarily coincide with greater rates of slope failure: Hancox and Wright (2005) and Gao and Maro (2010) both indicate how moderate slope angles were associated with the majority of slope failures due to regolith stripping of steeper slopes.

Climate regime: Climatic behaviour can strongly influence catchment connectivity, largely by determining the frequency and nature of extreme storm events, which are known to liberate and transport a disproportionate amount of sediment (Benda & Dunne, 1997; Fuller, 2007; Fuller, 2008; Fuller & Heerdegen, 2005). Along the East Coast region of New Zealand, rainfall events with a recurrence interval of one to two times per year and that deliver 200 mm of rainfall in 72 hours are considered to be significant events (Jones & Preston, 2012). It is thought that their high magnitude is sufficient to exceed geomorphological thresholds that 'normal' rainfall events are not capable of, and this can result in liberation of otherwise stable sediment sources within the catchment (Magilligan, 1992). For example, unusually high sediment loads have been observed to reach the fluvial system of an East Coast catchment, the Waipaoa catchment, during high-manitude rainfall events. (Fuller and Marden, 2010).

Catchment scale: A catchment can be broken down into building blocks of varying scale. Brierley and Fryirs (2008) elaborate on the importance of scale within a theory called "Hierarchical Patch Dynamics". The theory contends that catchment size has a strong affect on connectivity; as a larger catchment will generally have a longer distance between adjacent hierarchical patches (e.g. slope and channel domain). For connectivity to occur a greater amount of energy is needed to move sediment through larger catchments in comparison with a smaller catchment. Jones and Preston (2012) present this idea under the model of "Scale dependency". Their results displayed how as catchment size increased, sediment delivery ratios decreased. Their study was based on small sub-catchments within the Waipaoa basin where large-scale decoupling agents such as floodplains and river terraces, were not a factor. Larger catchments can have higher levels of potential energy stored; however, whether or not this is true for any particular catchment or whether or not the higher energy can counter the effect of scale dependency will depend on individual catchment characteristics.

Anthropogenic modification: Human colonisation has also modified catchment connectivity in New Zealand. European colonisations lead to the expansion of agriculture in the 1800s and the deforestation of a substantial amount of land across the country, including much of East Coast (Wilmshurst, 2001). Deforestation reduces slope stability and increases erodibility significantly, often leading to greatly enhanced rates of soil degradation and slope failures (e.g. Ebisemiju, 1990; Marden *et al*. 2005; Marden *et al*., 2012). Much of the sediments liberated through enhanced soil degradation and landsliding are subsequently incorporated into the fluvial system, increasing the level of sediment connectivity in those catchments.

Landslides & connectivity

A catchment sediment budget may be strongly influenced by slope failures (Benda & Dunne, 1997). Landslides can be described as (i) coupled, where they connect sediment to channels though debris tails; and (ii) buffered, where sediment is not directly delivered to the channel system (Hancox & Wright, 2005; Peart *et al*., 2005). Size differences between landslides types such as shallow landslides and gully mass movements also influences the extent of coupling. Shallow landslides are characterized by surface movements in the top soil or within highly erodible upper strata (Cruden & Varnes, 1996). Gully mass movements are typically deep seated (i.e. involve failure of the bedrock) and all of them border, or are part of, actively eroding gully networks. Gully mass movements are typically less widespread compared with shallow landslides; but, they can produce very large volumes of sediment because of their deep seated interactions with subsurface lithology and geological structures, and their proximity to the fluvial system; they have strong coupling with fluvial systems as they generally occur within the immediate vicinity of a channel (Beavis, 2000; Betts *et al*., 2003; Fuller & Marden, 2011). Differences in size for landslides of the same type also influences connectivity. Large shallow landslides are more likely to be connected to tributaries than smaller shallow landslides (Hancox & Wright, 2005).

Stronger links between the slope and channel domain increase sediment transfer and the ability for the fluvial system to change (Harvey, 2001). If catchment connectivity is strong due to extensive landslide events, river geomorphology is very likely to change (Hancox & Wright, 2005). Large sediment volumes introduced by enhanced coupling in the fluvial system may cause channel aggradation and an increase in channel complexity (Schwendel & Fuller, 2011). For example, after the 2004 Manawatu flood event, an increase in bar formation of 65-600% was observed in the Kiwitea, Oroua and Pohangina reaches within the Manawatu catchment, where substantial slope erosion and bank erosion had occurred (Fuller & Heerdegen, 2005); and following the 1999 Mt Adams Rock Avalanche and landslide-dammed outburst flood, extensive downstream aggradation, channel widening, and channel avulsions occurred in the Poerua River, with the effects continuing today (Hancox *et al*., 2005).

The disturbance of a natural equilibrium state in fluvial systems is followed by a recovery phase where sediment is redistributed until equilibrium is met (Fuller *et al*., 2003). Continual flood events can slow recovery (Harvey, 2001); however, recovery can be hastened by increasing slope stability and therefore reducing failures and the sediment budget (Kasai *et al*., 2005). Afforestation is the main technique used to encourage stability and recovery as root penetration can provide structural reinforcement and reduce slope wetness (Ziemer *et al*., 1981; Marden, 2004; Marden *et al*., 2005). However, Jones and Preston (2012) propose a model (based on Crozier and Preston, 1999) for how a landscape may move through phases of sediment input (landsliding) and establish a new equilibrium that entails stripping of colluvium towards a bedrock phase where landsliding ceases and gullying becomes the dominant process. In this case, thresholds governing slope stability gradually increase during a series of phases involving a reaction phase (after initial felling of forestry), interrupted relaxation phase (where colluvium rich foot-slopes undergo a second stage of landslide events and some top soil recovery on the upper slopes provides more landslide material); however if landsliding continues the landscape will move into the the bedrock phase (landsliding decreases as there is little top soil). Gomez *et al*. (2003) highlight how sediment legacies within the fluvial network in the Waipaoa catchment can take multiple generations to be re-worked and for channel equilibrium to be reached again. The literature leads to the conclusion that the key to understanding catchment recovery following widespread slope failure is to first understand the catchment-specific characteristics that condition thresholds and recovery rate. To date, few studies have attempted to specifically quantify the role that these characteristics play. The aim of this study was to quantify the extent of buffered and coupled landslide area cover in addition to assessing catchment recovery in relation to site-specific thresholds in the Houpoto Forest catchment.

Study Site

The Motu catchment (Fig. 1) hosts a large commercial forest, the Houpoto Forest, which has been under the management of Hancock Forestry and underwent its first harvest between 1/6/2007 and 1/2/2008. Replanting in a second rotation of pine began on 30/9/2009.

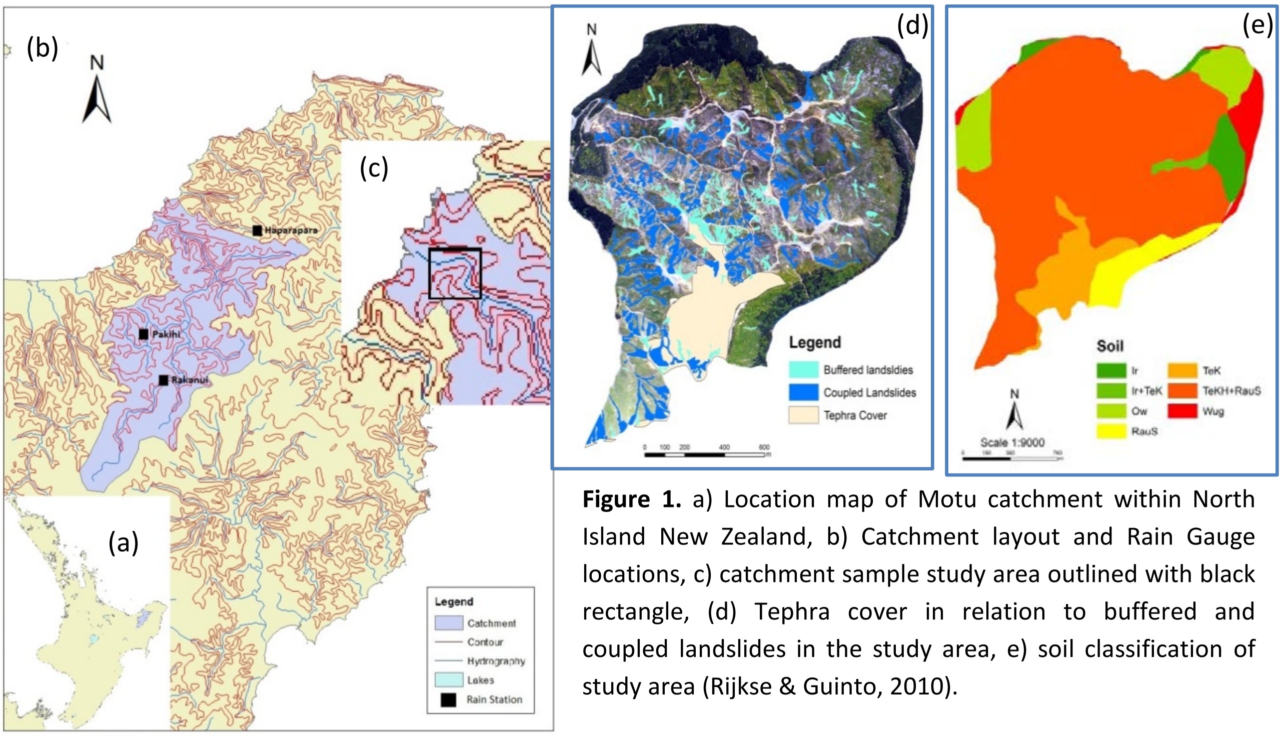

Figure 1. a) Location map of Motu catchment within North Island New Zealand, b) Catchment layout and Rain Gauge locations, c) catchment sample study area outlined with black rectangle, (d) Tephra cover in relation to buffered and coupled landslides in the study area, e) soil classification of study area (Rijkse & Guinto, 2010).

The study focussed on a small representative section of the total Houpoto Forest (Fig, 1.c) for which aerial photography was available to assess the impacts of forest harvesting on landsliding and catchment connectivity on the forested catchment as a whole. As with many of the landscapes of the north-eastern North Island, the terrain of the Houpoto Forest is highly erodible as a result of the poor induration of the bedrock in combination with unfavourable climatic conditions and tectonic setting of the Hikurangi Margin (Mazengarb & Speden, 2000; Kasai, 2006; Kamp, 1988). As a result, this catchment, like the entire East Coast, is characterized by large sediment budgets and high aggradation rates (Jones & Preston, 2012; Marden *et al*., 2012).

Tectonic setting: The catchment investigated here is part of the East Coast region within the Hikurangi Margin of New Zealand (Kamp, 1988). Tectonism, associated with plate boundary processes, has produced an array of strike-slip faults and fault zones within the axial ranges of the Hikurangi Margin. The faulting has weakened the Mesozoic greywacke and calcareous mudstones, rendering this terrain susceptible to landsliding (e.g. Brook and Hutchinson, 2008; Marden, 1984).

Lithology and soil type

The geology of the Houpoto Forest comprises predominantly early Quaternary and late-Jurassic to Cretaceous sandstones and mudstones from the Tauranga group and Waioeka Group respectively; these rocks are typically poorly indurated, rendering them highly erodible. The predominant soil cover is a combination of Tekaha Hill soils (Ir+ Tek, Tek) and Raukituri Sands (RauS) (Fig. 1). Both soils are moderately to highly suitable for forestry (Rijkse & Guinto, 2010). Soil type is relatively consistent across areas where landslides have been mapped. Throughout the forest as a whole, a prevalence of landsliding associated with tephras has been observed (R. Black personal communication, 2013). However, within the specific part of the catchment studied (Fig. 1c), tephra does not appear to be present as a dominant soil cover or strongly associated with landsliding (Fig.1e).

Climate

The East Coast of New Zealand is characterized by a humid temperate climate (Fuller & Marden, 2010). The majority of rainfall occurs during the winter months from May to August (Reid & Page, 2002). In addition to higher intensity and volume rainfall during the winter months, cyclonic activity has induced larger storms within the summer months (Page *et al*., 1994; Kelliher *et al*., 1995). During the study period 2007-2013 there have been five major rainfall events where rainfall has exceeded 200 mm/day.

Methods and Results

Landslide mapping methodology

Landslide quantification and analysis was completed through digitization and statistical analysis (cf. He & Beighley, 2007). Ortho-rectified photography from 2007-2013, was sourced from Hancock Forest Management, and overlayed with 20 m contours (LINZ) in a GIS (ArcMap 10) to enable digital mapping of landslides. A site boundary polygon was set around all images, in order to keep a consistent area for calculating the percentage of landslide plan-area. Active coupled and buffered landslides were individually mapped for each year. Identification and mapping of areal extent of landslides was based on visual assessment of vegetation cover (or lack thereof indicating recent disturbance), exposed soil colouration in imagery (indicative of recent regolith stripping), and slope, landslide scars (identified by arcuate scarps or depressions) and deposits (identified by debris accumulations downslope from scars). Care was taken to record only new (fresh) landslides appearing for the first time in each image; however, it is recognised that some landslides may have been missed if they occurred in the same locations as previous landslides. Landslides were classified as 'buffered' if the debris deposits were not connected to any stream channels, whereas landslides whose debris deposits appeared to enter a channel were classed as 'coupled'. Data were transferred to excel and graphed accordingly to display variations in buffered and coupled landslides.

Landslide mapping results

June 2007-February 2008

No landslides were observed in the earliest image (June 2007). The forest cover was complete in this image, consistent with felling data provided by Hancock Forestry management. Between June 2007 and February 2008 harvesting of the area was undertaken, with felling completed by late February 2008. There are no visable landslides present within both sets of imagery; however there is evidence of pull tracks from log recovery in February 2008 (Figs. 2 and 3).

February 2009

Fresh landslides were visible over 9.12% of the total site area in the February 2009 image, indicating slope instability commencing within about 12-18 months since logging began. Most failures occurred along logging tracks and log pull tracks. Overall buffered landslides covered a larger area than coupled landslides. Buffered landslides covered 5.2% of the total site area versus coupled landslides which covered 3.92% (Fig. 3).

November 2010

A sizeable increase in landslide areal coverage compared with February 2009, was observed in the November 2010 imagery (14.13%, providing an increase of 5.2%). Furthermore, landslide areal coverage of the coupled landslides rose from 3.92% in 2009 to 10.10% in the 2010 image. Buffered landslide area coverage was half that of coupled area (4.03%), and was slightly smaller than in the previous (2009) image.

April 2011- April 2012- February 2013

Fewer landslides were observed in the subsequent images from 2011 through to 2013 (Fig. 3). There was a 1.0% reduction in buffered landslide areal coverage and a substantial 6.29% reduction in coupled landslide coverage between April 2011 and April 2012. Coupled landslide coverage also decreased at a faster rate than buffered landslides (3.81% in 2011, 1.59% in 2012 and 0.9% in 2013).

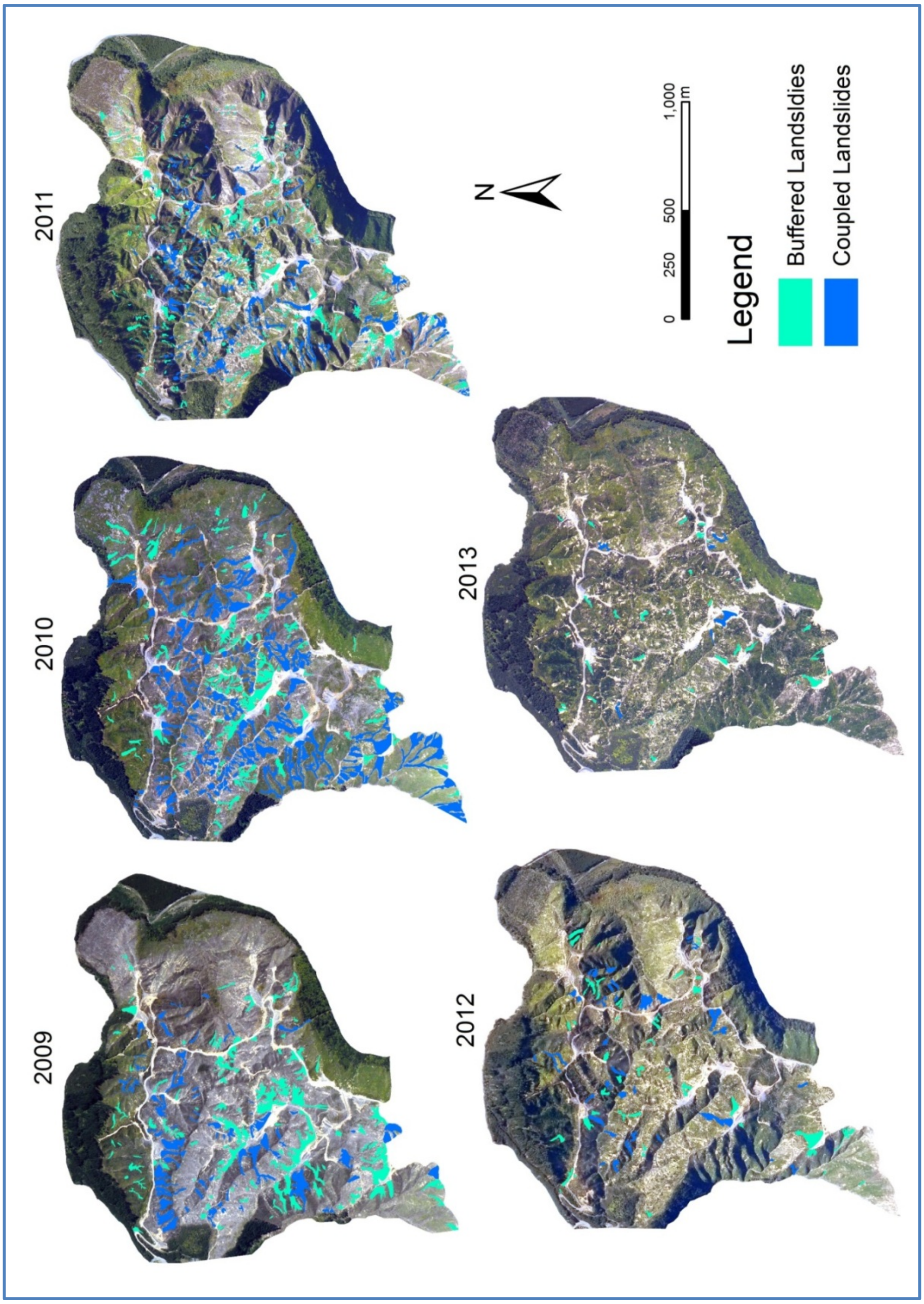

Figure 2: Buffered and coupled landslide cover 2007-2013

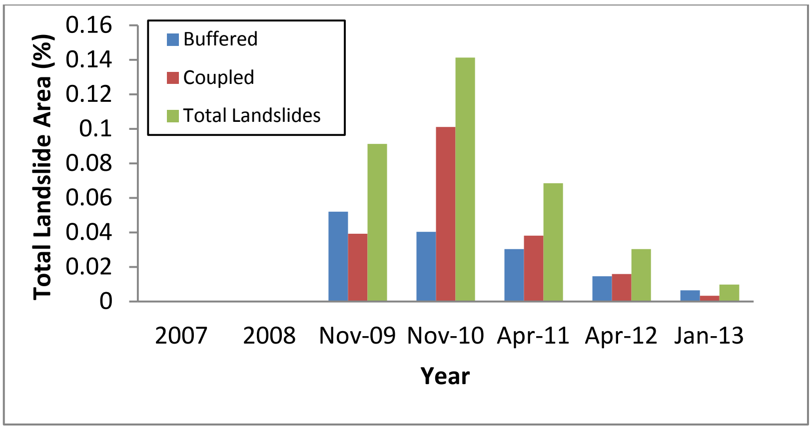

Figure 3. Aerial extent of buffered and coupled landslides as a percentage of the total study area, identified between 2007-2013.

Rainfall

To assess the impacts of deforestation on slope instability it is also necessary to consider the frequency and magnitude of triggering events that followed deforestation. Heavy rainfall events are a common trigger for landslides and as such rainfall data are important to consider within landslide initiation analysis (Lan *et al.,* 2005; Guzetti *et al.,* 2008; Tsai & Yang, 2006; Brunetti *et al.,* 2010). Rainfall data were sourced from the Bay of Plenty Regional Council from the Haparapara, Rakanui and Pakahi Rain stations. Five major events were observed (Fig. 4, Table 1). All events had the potential power to exceed geomorphic thresholds and initiate landsliding (rainfall exceeding 200 mm/day). However, the amount of landsliding was not consistent across all rainfall events (Table 1). A ten day wetness index was calculated from each major rainfall event (exceeding 200 mm/day). A ten day index provides a better understanding of antecedent rainfall before a potential triggering event in comparison to a 24/48 hr rainfall total (Jones & Preston, 2012), since rainfall does not necessarily fit within a 24 or 48 hour period. The wetness index was calculated from data collected by the rain gauge closest to the site, the Pakihi Station (cf. Fig. 1). The index was calculated using equation 1 (Table 1).The largest index occurs in 2010 and high values also are observed in 2010 and 2011. Higher wetness intervals also coincide with higher landslide cover.

$$WI = \frac{cumulative\ rainfall}{10\ days} \quad \text{[Eq. 1]}$$

Table 1. Major rainfall events and Wetness index recorded at Haparapara rain station. The date given under 'Imagery' indicates which image the rainfall event impacts (i.e. landslides) were captured in.

Imagery	Date of major rainfall event	Total rainfall of event (mm)	Cumulative rainfall (mm)	Wetness Index	Site landslide areal coverage (%)
2009	N/A	N/A	N/A	N/A	N/A
2010	20/02/2009	277	445	44.45	9.12
2010	14/08/2010	267	218	21.8	14.13
2011	12/05/2011	207	401	40.1	6.85
2011	26/05/2011	282	298	29.8	6.85
2012	16/9/2012	217	312	31.2	3.04
2013	N/A	N/A		N/A	0.98

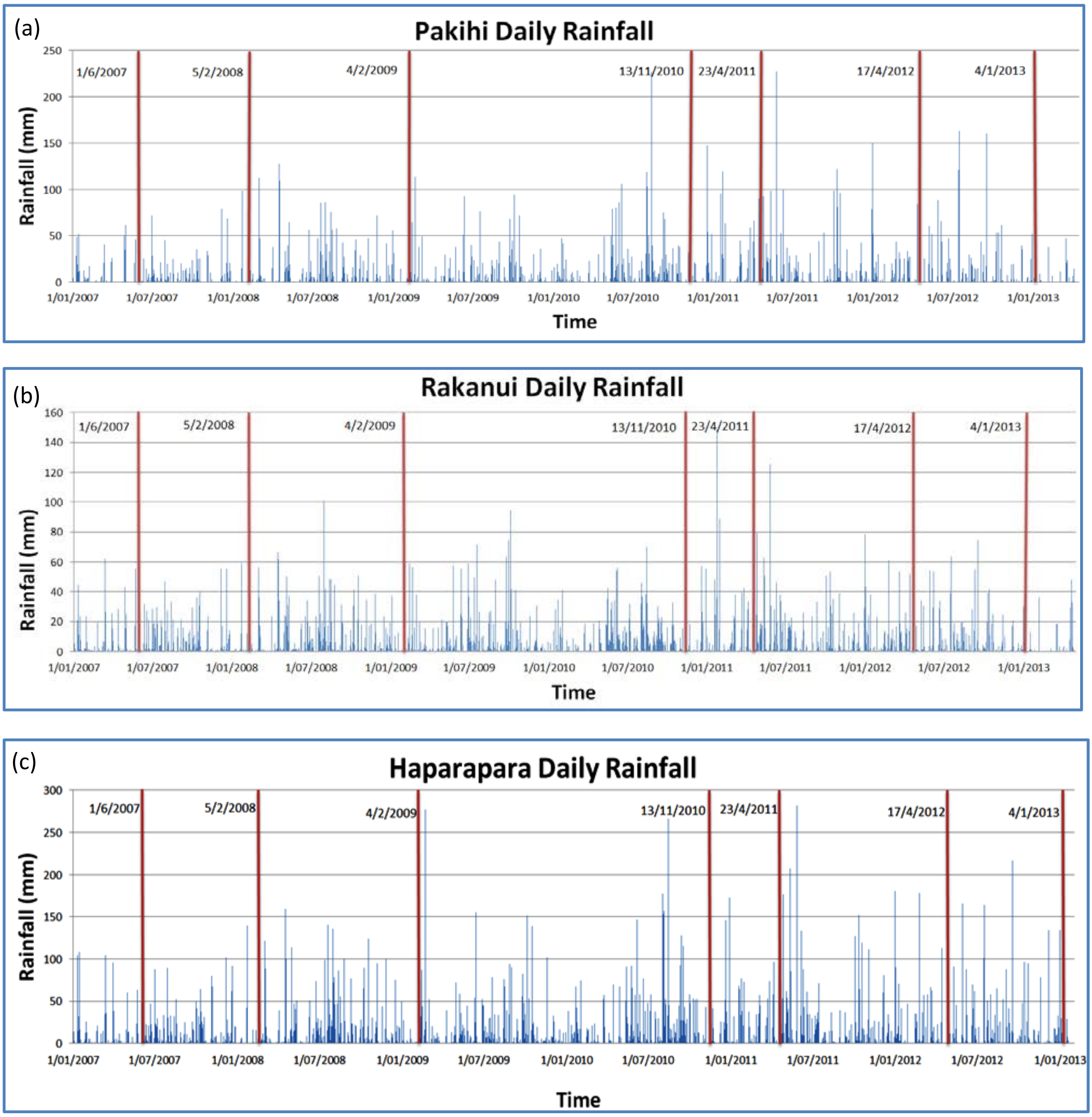

Figure 4. Daily rainfall a) Pakahi rain station; b) Rakanui rain station c) Haparapara rain station. Vertical red bars indicate the dates for aerial photographs used in this study.

The rainfall records show several high magnitude events, none of which are captured in the 2009 image.

Geology

Geological information was overlaid with the distribution of buffered and coupled landslides to assess the extent to which lithology may exert control or condition landslide distribution and slope-channel coupling. The indurated sandstones and mudstone of the Torlesse group and the weakly lithofied and sheared Quaternary strata both coincided with landslide events (Mortimer, 1994). Landslide areal coverage was 380% greater within the Torlesse group than the Quaternary lithology, adjusted for differences in contributing area of the two rock types. Within the Holocene group there are few to no landslides recorded in the imagery (Figs. 5 & 6; Table 2).

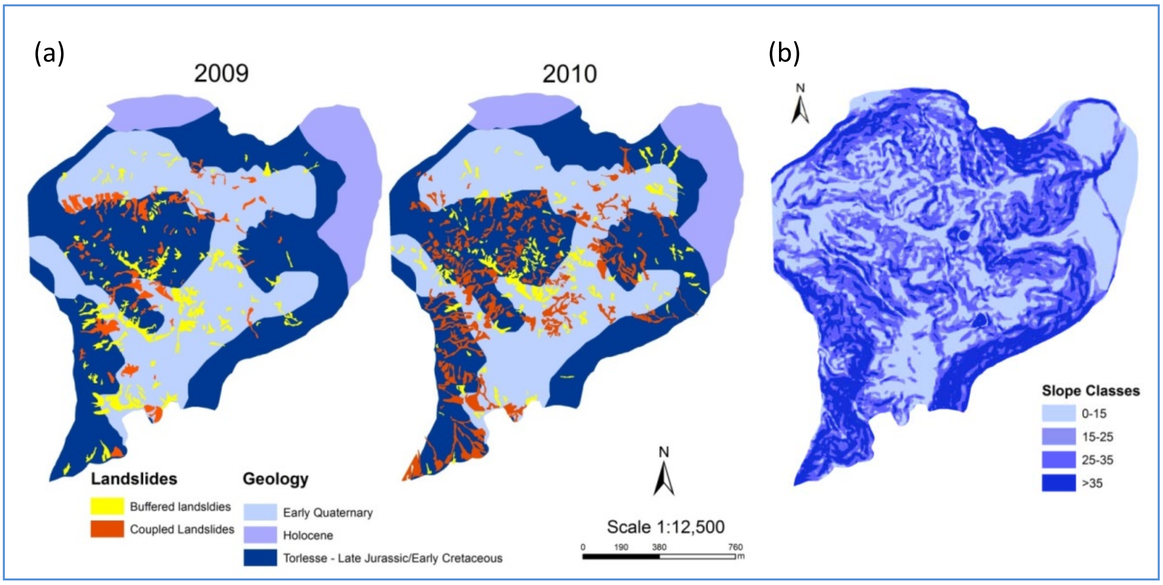

Figure 5. (a) Landslides overlain on site geology, 2009 and 2010, (b) distribution of slope classes (°)

Table 2. Proportional percentage of coupled and buffered landslides intersecting with individual geological group areas (m²). C.L: Coupled Landslides. B.L: Buffered Landslides

Geological Age	C.L 2009	B. L 2009	C.L 2010	B.L 2010	C.L 2011	B.L 2011	C.L 2012	B.L 2012	C.L 2013	B.L 2013
Early Quaternary	3.85	6.00	7.03	4.63	4.21	3.65	1.76	1.97	0.57	0.93
Holocene	0.00	0.00	0.00	0.03	0.00	0.09	0.00	0.00	0.00	0.00
Late Jurassic-Early Cretaceous	15.55	16.47	50.84	13.86	14.25	11.06	5.83	3.86	0.44	1.51

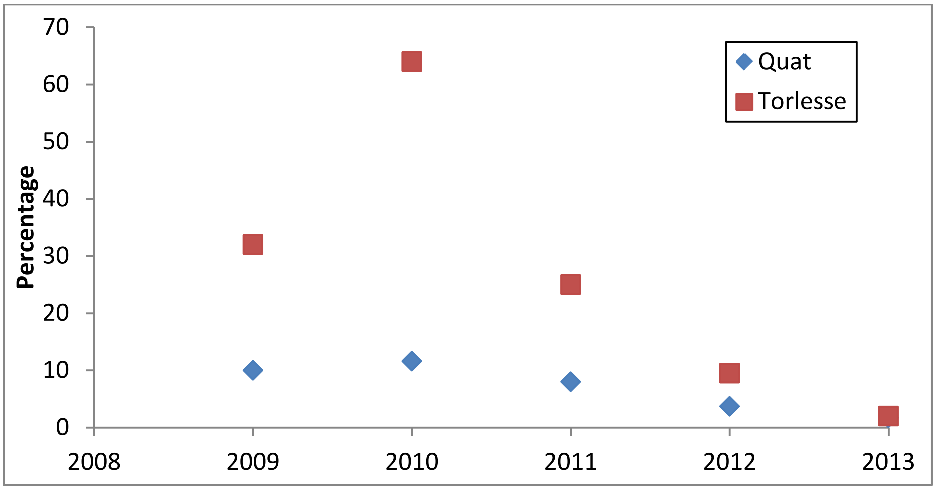

Figure 6. Proportional percentage of coupled and buffered landslides intersecting with individual geological group areas (m²) based on Table 2.

Slope Class

Analysis using slope class mapping has previously provided insight into landslide characteristics (Hancox & Wright, 2005; Saha *et al.,* 2005; DeRose, 2013). Slope class mapping involves the classification of land based on slope angle. The purpose of analysing slope class in this study was to try to quantify to what extent topography controlled both the initiation conditions of the landslide and the runout of the landslides (and therefore connectivity). However, because the landslide mapping undertaken in this study was not done in sufficient detail to separate source areas from deposits, the slope class analysis here was based on an aggregate of the slope classes underlying the source areas and deposits. This limits the certainty in these analyses but nonetheless provides a crude indication of the role of topography in landslide initiation and connectivity. Slope class shapefiles sourced from Hancock Forest Management were used to create a slope class map (Fig 5b). The slope classes were intersected with buffered and coupled landslide areas from the years 2009-2013 (Fig. 7). The landslide area coinciding with slope classes was the proportion of landslide area calculated for each class. Slope classes containing the highest landslide area were at 25-35˚ from 2009-2011 and 15-25 ˚ from 2011-2013.

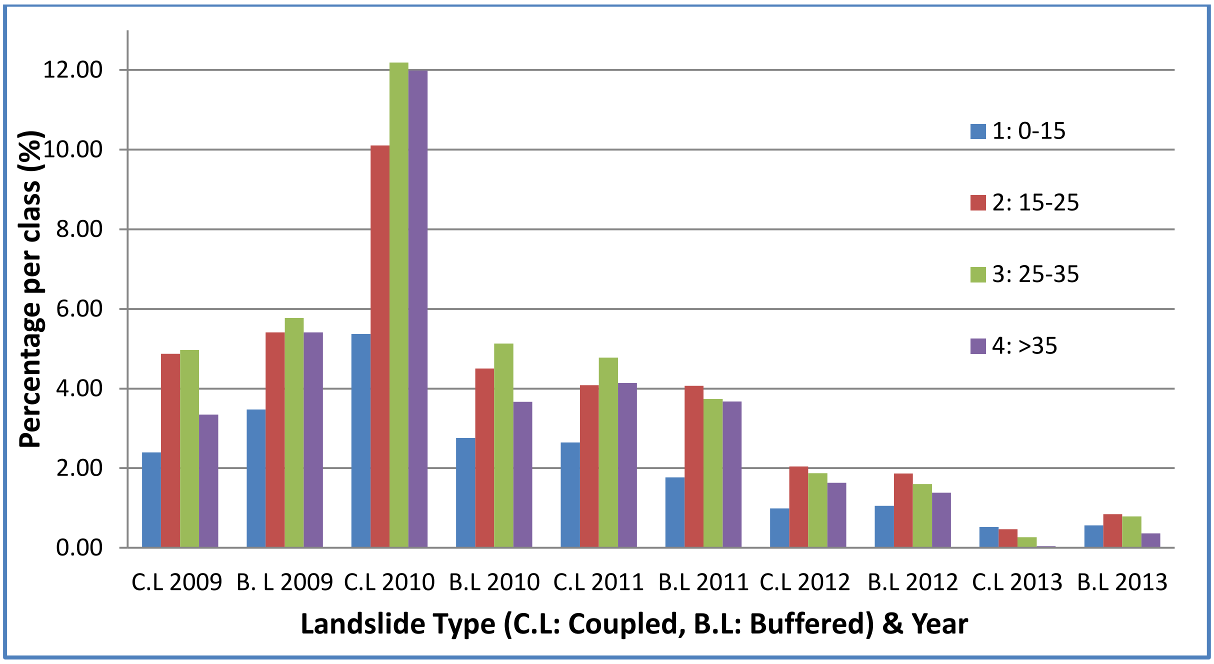

Figure 7. Percentage of buffered and coupled landslide cover per slope class.

Discussion

For slope failure to occur, a stability threshold, often assessed as the ratio of shear strength to shear stress, must be exceeded (Schumm, 1979; Massey, 2010; Glade *et al.,* 2005). A myriad of factors have contributed to the exceedence of this threshold in parts of the Houpoto Forest over the study period. The main factors include the weak geology and overlying regolith cover, high magnitude rainfall, and steep unvegetated slopes; this unfavourable combination of factors has been the cause of landsliding in many landscapes (e.g. Marden, 2004; Fryirs *et al.,* 2007; Fryirs, 2012). The following section discusses these factors in greater detail, as well as the role of dynamic factors that changed the stability of the slope.

Weakly lithofied mudstone and sandstones units are characteristic of the East Coast (Mazengarb & Speden, 2000; Phillips *et al.,* 2007). They are also identified as key preconditioning factors to slope instability (Kasai, 2006; Fuller & Marden, 2008; Fuller & Marden, 2010). Lithological variation appears to have influenced landslide distribution in this study (greater extent of landsliding in the Torlesse Group, cf. Fig. 6), but reason for the influence is probably indirectly related to the geology, and instead related to topographic and vegetation differences. The Quaternary lithology appears to occupy flatter terrain within the valley floors compared with the Torlesse rocks - the Quaternary sediments are less likely to have been deposited or preserved on the steeper slopes. Most of the Holocene materials occupy flatter terrain along the ridges, and also fall outside of the areas that were felled (therefore having higher slope stability through the root penetration and rain interception provided by the vegetation). Thus there is reason to suspect that the differences in landslide extent between different lithologies in this study is an artifact of the morphology and the small size of the catchment; this needs to be confirmed with further analysis but it is beyond the scope of this study.

Slope angle is a preparatory factor that is changed via long term slope degradation and steepening and anthropogenic slope modification (Marden, 1984; Wilmshurst, 1997). Two useful questions to answer are: 1) What slope classes facilitate landsliding? 2) What slope class defines the angle of restitution and therefore connectivity? Because of mapping limitations within this study, it has not been possible to provide a firm answer to these questions. Instead, an attempt was made to gain an initial indication of this by examining which slope classes contain the largest landslide areas and by comparing coupled and buffered landslides. As expected, there was generally a higher incidence of landslides (initiation and deposition) on the three highest slope classes compared to the very lowest slope class (Fig. 7). The absence of failures on the lower gradient slopes can be explained by low shear stresses that are unlikely to overcome the material strength even under saturated conditions (Craig, 1997; Hennrich & Crozier, 2003). An interesting finding is that the slope class containing the highest landslide area was 25-35˚ from 2009-2011, but 15-25˚ from 2011-2013. This could be an indication that failure sites on steeper slopes were being exhausted. On steeper slope regolith stripping from previous slope failure tends to limit landsliding on steeper gradients (cf. Gao & Maro, 2010; Jones & Preston, 2012). It is also possible that the materials deposited by these events were becoming the failure sites for subsequent events. There was no clear distinction between the slope classes that produced buffered versus coupled landslides, even though it is expected that steeper slope angles would produce more coupling (i.e. longer runout distances) (e.g. Hancox & Wright, 2005); greater slope gradients not only encourage landslide events, but also induce larger landslides as there is more potential energy (Schumm & Lichty, 1965; Glade *et al.,* 2005; Jones & Preston, 2012). The absence of this relationship being apparent may be a result of the conflation of both the source areas and deposits in this landsliding mapping. Subsequent research to overcome that limitation in this study could include the separation of the landslides into their source areas and their deposits before measuring slope angle. A simpler alternative could be to measure the slope angle at the head of the landslide and the distal end of the debris tail. These analyses would be improved with the use of a more detailed slope map produced from a high-resolution digital elevation model (DEM).

Vegetation cover also has a strong influence on landslide susceptibility and recovery (Ziemer, 1981; Marden, 2004; Glade *et al.,* 2005). Change in landslide coverage has occurred since the felling of forestry in 2007-2008 and also after the re-planting of forestry August 2009. Slope failure thresholds are assumed to have been significantly lowered through deforestation as top soils were left open and susceptible to soil degradation (e.g. less interception of rainfall), in addition to the lowering of shear strength previously enhanced by root penetration, both of which have been factors considered elsewhere (e.g. Ekanayake & Phillips, 1999; Marden, 2004, Marden *et al.*, 2011; Marden *et al.,* 2012). Stronger coupling occurs in the absence of vegetation because landslide events are larger and more frequent, and can travel farther because of a reduction in flowpath obstacles; subsequently sediment supply and connectivity increases (Fryirs *et al.,* 2007; Fryirs, 2012).

The benefits of replanting during November 2009 are seen in the fast recovery rate of the slope domain in 2011 after the devastating landslide coverage displayed in the 2010 imagery (Figs. 2 and 3). Canopy closure of a maturing forest increases rainfall interception, reduces the effects of weathering on bare exposed soils, in addition to enhancing shear strength and slope stability (Preston & Crozier, 1999; Marden *et al.*, 2005). The development of root reinforcement has continued to increase shear strength and reduce landslide events and encourage recovery (Fig. 2). As stability was regained (2011-2013), landslide events decreased, despite continued incidence of high-magnitude rainfall events (2011 containing a wetness index of 40.1 close to the 45.45 index observed in 2010 imagery), and in turn catchment connectivity has progressively reduced (cf. Gomez *et al.,* 2003; Fuller & Marden, 2008).

Although deforestation greatly increases the likelihood of landslides events, sediment supply and slope channel coupling, failure still requires a trigger, which in this case was heavy rainfall as observed elsewhere (e.g. Glade, 1997; Fuller & Marden, 2011; Marden, 2011). Felling began in June 2007, but no landslides were visible in 2009 (Fig. 2) despite many rain days occurring (Fig. 4). These rainfall events were not large enough to trigger failure even with a reduced vegetation cover. Landslides did not seem to be initiated until the amount of daily rainfall exceeded about 200 mm; these rainfall events were considered to be extreme magnitude rainfall events, following the methodology of Jones & Preston (2012). All of the extreme events had the potential to exceed geomorphic thresholds and initiate landsliding, but the extent of landsliding in these events varied. The largest areal coverage of landslides was observed in 2010, but larger extreme rainfall events occurred after this period.

One interpretation for the reduction in landsliding in the latter extreme events is the partial recovery of slope stability through growth of the re-planted forestry). During the period between 2009-2010 (where the largest landslide areal cover was observed) slope stability had deteriorated through deforestation and the very young, recently re-planted forestry could not provide sufficient strength through root penetration; these observations are supported by other research (e.g. Ziemer, 1981; Ekanayake & Phillips, 1999; Marden, 2004; Glade *et al.,* 2005; Marden *et al.*, 2011; Marden *et al.,* 2012). The catchment was highly vulnerable and rainfall events provided the energy to exceed slope stability thresholds and induce landsliding.

Another factor that influences the likelihood of slope failure during an extreme rainfall event is antecedent rainfall. Crozier & Eyles (1980) proposed the idea of an Antecedent Water Status model where preceding rainfall in addition to the significant event are taken into consideration when analyzing landslide initiation thresholds (Crozier, 1999, Glade *et al.,* 2000). The wetness index is consistently high across 2009, 2010 and 2011, where there are higher levels of landslide activity. A wetness index of 45.5 is achieved between capture of the 2009 and 2010 images, and a high incidence of landslides was observed in this period. The antecedent rainfall in the days leading up to the extreme rainfall event of 4/08/2010 could thus have caused landslides to be initiated at a lower daily rainfall threshold for that rainfall event, and thus increased the number of landslides that occurred (Fig. 4).

High magnitude rainfall results in widespread landsliding and therefore increases sediment supply and slope-channel connectivity. In addition to this, a larger energy source enables sediment transfer downslope and from slope to channels. If slope stability was not regained through replanting, repeated rainfall events, even of low magnitude, would continue to increase sediment supply and connectivity. Low-magnitude events would be more capable of moving sediments already liberated by landsliding left behind on the slopes or liberate easily erodible material left in the landslide scars (Wolman & Miller, 1960; Gardener, 1977; Fryirs *et al*., 2007). Connectivity through landsliding seems to have been driven by large rainfall events as indicated by the areal extent of landslides being highest after rainfall events in 2010. This is also consistent with findings elsewhere in the wider East Coast region (Fuller & Marden, 2011), especially if slope stability is not regained through immediate replanting. However, future research on landslide run out and conveyance energy, in conjunction with improved slope class data would provide a better understanding of landslide sediment connectivity.

Conclusion

Connectivity through shallow landsliding has fluctuated between 2007-2013 within the Houpoto Forest. The weak lithology and abundance of moderately-steep slopes makes the site susceptible to landsliding. Forest harvesting is thought to have further lowered the thresholds for slope failures, and increased the landslide abundance during several high-magnitude rainfall events. High antecedent rainfall prior to high magnitude rainfall events is assumed to have resulted in increased landslides between 2009 and 2010. High rainfall events occurred in later years during 2011-2013, however, progressively fewer landslides were triggered which is presumed to be a reflection on the gradual recovery of the hillslopes; the growing vegetation provided increasingly greater interception of rainfall and slope stability. These results confirm that immediate planting after cutover helps provide fast recovery of the Houpoto Forest slopes and reduce slope-channel connectivity. Slope channel coupling will continue to fluctuate as anthropogenic and geomorphological preparatory factors adjust geomorphic thresholds. Future research on the proximity of tributaries to the slope domain, in addition to improved slope classification and analysis could provide a deeper understanding of the angle of restitution, landslide run out and the energy needed for conveyance and coupling.

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References

Benda, L. & Dunne, T. (1997). Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. *Water Resources Research,* **33,** 2849-2863.

Betts, H.D., Trustrum, N.A. & De Rose, R.C. (2003). Geomorphic changes in a complex gully system measured from sequential digital elevation models, and implications for management. *Earth Surface Processes and Landforms,* **28,** 1043-1058.

Bracken, L.J. & Croke, J. (2007). The concept of hydrological connectivity and its contribution to understanding runoff dominated geomorphic systems. *Hydrological Processes,* **21,** 1749-1763.

Brierley, G.J. & Fryirs, K.A. (2008). *River Futures: An Integrative Scientific Approach to River Repair.* Society for ecological restoration international: Island Press, London.

Brook, M.S. & Hutchinson, E. (2008). Application of rock mass classification techniques to weak rock masses: A case study from the Ruahine Range, North Island, New Zealand. *Canadian Geotech,* **45,** 800-811.

Brunetti, M.T., Peruccacci, S., Rossi, M., Luciani, S., Valgi, D. & Guzzetti, F. (2010). Rainfall thresholds for the possible occurrence of landslides Italy. *Natural Hazards Earth Science,* **10,** 447-458.

Church, M. (2002). Geomorphic thresholds in riverine landscapes. *Freshwater Biology,* **47,** 541-557.

Craig, R.F. (1997). *Soil Mechanics*. Spon Press, London. pp. 485.

Crozier, M.J. (1999). Prediction of rainfall-triggered landslides: A test of the antecedent water status model. *Earth Surface Processes and Landforms,* **24,** 825-833.

Crozier, M.J. & Eyles, R.J. (1980). Assessing the probability of rapid mass movement. In *Third Australia-New Zealand Conference on Geomechanics: Wellington, May 12-16, 1980* (p.2). Institution of Professional Engineers New Zealand.

Crozier, M.J. & Preston, N.J. (1999). Modelling changes in terrain resistance as a component of landform evolution in unstable hill country. In: Hergarten, S., Neugebauer, H.J. (Eds.), *Process Modelling and Landform Evolution*, Lecture Notes in Earth Sciences 78. Springer, Berlin/Heidelberg/New York, pp. 267–284.

Cruden, D.M. & Varnes, D.J. (1996). Landslide types and processes. *Landslides: investigation and mitigation*, **247,** 36-75.

DeRose, R.C. (2013). Slope control on the frequency distribution of shallow landslides and associated soil properties, North Island, New Zealand. *Earth Surface Processes & Landforms*, 38, 356-371.

Ebisemiju, F.S. (1990). Sediment delivery ratio prediction equation for short catchment slopes in humid tropical environment. *Journal of Hydrology,* **114**, 191-208.

Ekanayake, J.C., & Phillips, C.J. (1999). A method for stability analysis of vegetated hillslopes: an energy approach. *Canadian Geotech,* **36,** 1172-1184.

Fryirs, K.A. (2012). (Dis)Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. *Earth Surface Processes and Landforms,* **38,** 30-46.

Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai. (2007). Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Catena,* **70,** 49-67.

Fuller, I.C. (2007). Geomorphic work during a “150-Year” storm: Contrasting behaviors of river channels in a New Zealand catchment. Annals of Association of American Geographers, **97,** 665-676.

Fuller. I.C. (2008). Geomorphic impacts of a 100-year flood: Kiwitea Stream, Manawatu catchment, New Zealand. *Geomorphology,* **98,** 84-95.

Fuller, I.C., & Heerdegen, R.G. (2005). The February 2004 floods in the Manawatu, New Zealand: hydrological significance and impact on channel morphology. *Journal of Hydrology,* **44,** 75-90.

Fuller, I.C., Large, A.R.G. & Millan, D.J. (2003). Quantifying channel development and sediment transfer following chute cutoff in a wandering gravel-bed channel. *Geomorphology,* **54,** 307-323.

Fuller, I.C. & Marden, M. (2008). Connectivity in steep-land environments: gully-fan coupling in the Tarndale system, Waipaoa catchment, New Zealand. *Sediment Dynamics in Changing Environments, IAHS Publ.* ***325****, 275-282.*

Fuller, I.C. & Marden, M. (2010). Rapid channel response to variability in sediment supply: Cutting and filling of the Tarndale Fan, Waipaoa catchment, New Zealand. *Marine Geology,* **270,** 45-54.

Fuller, I.C. & Marden, M. (2011). Slope-channel coupling in steep land terrain: A field-based conceptual model from the Tarndale gully fan, Waipaoa catchment, New Zealand. *Geomorphology,* **128,** 105-115.

Gao, J. & Maro, J. (2010). Topographic controls on evolution of shallow landslides in pastoral Wairarapa, New Zealand, 1979-2003. *Geomorphology,* **114,** 373-381.

Gardener, J.S. (1977). Some geomorphic effects of a catastrophic flood on the Grand River, Ontario. *Canadian Journal of Earth Science,* **14,** 2294-2300.

Glade, T. (1997). Establishing the frequency and magnitude of landslide-triggering rainstorm events in New Zealand. *Environmental Geology,* **35,** 160-174.

Glade, T., Anderson, M. & Crozier, M.J. (2005). *Landslide Hazard and Risk.* J. Wiley, England.

Glade, T., Crozier, M. & Smith. P. (2000). Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical “Antecedent Daily Rainfall Model”. *Pure and Applied Geophysics,* **157,** 1059-1079.

Gomez, B., Banbury, K., Marden, M., Trustrum, N.A., Peacock, D.H. & Hoskin, P.J. (2003). Gully erosion and sediment production: Te Weraroa Stream, New Zealand. *Water Resources Research,* **39,** 1187-1201.

Guzetti, F., Peruccacci, S., Rossi, M. & Stark, C.P. (2008). The rainfall intensity- duration control of shallow landslides and debris flows: an update. *Landslides,* **5,** 3-17.

Hancox, G.T. & Wright, K. (2005). Analysis of landsliding caused by the February 2044 rainstorms in the Wanganui-Manawatu hill country, southern North Island, New Zealand. *Institute of Geological & Nuclear Sciences, Report.*

Hancox, G.T., McSaveney, M.J., Manville, V. & Davies, T.R. (2005). The October 1999 Mt Adams rock avalanche and subsequent landslide dam-break flood and effects in Poerua river, Westland, New Zealand. *New Zealand Journal of Geology and Geophysics*, **48**, 683-705.

Harvey, A.M. (2001). Coupling between the slopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. *Catena*, **42,** 225-250**.**

He, Y. & Beighley, R. E. (2007). GIS-based regional landslide susceptibility mapping: a case study in southern California. *Earth Surface Processes and Landforms,* **33,** 380-393.

Hennrich, K. & Crozier, M. (2004). A hillslope hydrology approach for catchment-scale slope stability analysis. *Earth Surface Processes and Landforms,* **29,** 599-610.

Jones, K.E. & Preston. (2012). Spatial and temporal patterns of off-slope sediment delivery for small catchments subject to shallow landslides within the Waipaoa catchment, New Zealand. *Geomorphology,* **141,** 150-159.

Kamp, P.J. (1988). Tectonic geomorphology of the Hikurangi Margin: surface manifestations of the different modes of subduction. *Geomorphology,* **69,** 55-67.

Kasai, M. (2006). Channel processes following land use changes in a degrading steep headwater stream in North Island, New Zealand. *Geomorphology,* **81,** 421-439.

Kasai, M., Brierley, G.J., Page, M.J., Marutani, T. & Trustrum, N.A. (2005). Impacts of land use change on patterns of sediment flux in Weraamaia catchment, New Zealand. *Catena,* **64,** 27-60.

Kelliher, F.M., Marden, M., Watson, A.J. & Arulchelvam, I.M. (1995). Estimating the risk of landsliding using historical extreme river flood data. *Journal of Hydrology* (*NZ*), **33**, 123–129.

Lan, H.X., Lee, C.H., Zhou, C.H. & Martin, C.D. (2005). Dynamic characteristics analysis of shallow landslides in response to rainfall event using GIS. *Environmental Geology,* **47,** 254-267.

Magilligan, F.J. (1992). Thresholds and the spatial variability of flood power during extreme floods. *Geomorphology,* **5,** 373-390.

Marden, M. (1984). *Geology and its relationship to erosion in the southern Ruahine Range, North Island, New Zealand.* Unpublished PhD Thesis, Massey University, Palmerston North.

Marden, M. (2004). Future proofing erosion-prone hill country against soil degradation and loss during large storm events: have past lessons been heeded. *New Zealand Journal of Forestry,* ***49,*** 11-16.

Marden, M., Arnold, G., Gomez, B. & Rowan, D. (2005). Pre and post-reforestation gully development in Mangatu forest, East Coast, North Island, New Zealand. *River Research and Applications,* **21,** 757-771.

Marden, M., Arnold, G., Seymour, A. & Hambling, R. (2012). History and distribution of steep land gullies in response to land use change, East Coast Region, North Island, New Zealand. *Geomorphology,* **153,** 81-90.

Marden, M., Hergzig, A. & Arnold, G. (2011). Gully degradation, stabilisation and effectiveness of reforestation in reducing gully-derived sediment, East Coast region, North Island, New Zealand. *New Zealand Hydrological Society,* **50,** 19-36.

Marutani, T., Kasai, M., Reid, L.M. & Trustrum, N.A. (1999). Influence of storm-related sediment storage on the sediment delivery from tributary catchments in the upper Waipaoa River, New Zealand. *Earth Surface and Processes and Landforms*, **24,** 881-896.

Massey, C. (2010). *The dynamics of reactivated landslides: Utiku and Taihape, North Island, New Zealand*, Doctoral thesis, Durham University.

Mazengarb, C. & Speden, I.G. (Eds.). (2000). *Geology of the Raukumara area* (Vol. 6). Institute of Geological & Nuclear Sciences.

Mortimer, N. (1994). Origin of the Torlesse Terrane and Coeval Rocks, North Island New Zealand. *International Geology Review,* **36,** 891-910.

Page, M.J., Trustrum, N.A. & DeRose, R.C. (1994). A high resolution record of storm-induced erosion from lake sediments, New Zealand. *Journal of Paleolimnology*, **11**, 333-348.

Phillips, J.D., Marden, M. & Gomez, B. (2007). Residence time of alluvium in an aggrading fluvial system. *Earth Surface Processes and Landforms,* **32,** 307-316.

Peart, M.R., Ng, K.Y. & Zhang, D.D. (2005). Landslides and sediment delivery to a drainage system: some observations from Hong Kong. *Journal of Asian Earth Sciences,* **25,** 821-836.

Preston, N.J. & Crozier, M.J. (1999). Resistance to shallow landslide failure through root-derived cohesion in east coast hill country soils, North Island, New Zealand. *Earth Surface Processes and Landforms,* **24,** 665-675.

Reid, L.M. & Page, M.J. (2002). Magnitude and frequency of landsliding in a large New Zealand catchment. *Geomorphology,* **49,** 71-88.

Rijkse, W.C. & Guinto, D.F. (2010). *Soils of the Bay of Plenty. Volume 3: Eastern Bay of Plenty.* Environmental Publication, New Zealand.

Saha, A.K., Gupta, R.P., Sarkar, I., Arora, M.K. & Csaplovics, E. (2005). An approach for GIS-based statistical landslide susceptibility zonation: with a case study in Himalayas. *Landslides,* **1,** 61-69.

Schumm, S.A. (1979). Geomorphic thresholds: the concept and its applications. *Transactions of the Institute of British Geographers,* 485-515.

Schumm, S.A. & Lichty, R.W. (1965). Time, space and casualty in geomorphology. *American Journal of Science,* **263,** 110-119.

Schwendel, A.C. & Fuller, I.C. (2011). Connectivity in forested upland catchments and associated channel dynamics: The eastern Ruahine Range. *Journal of Hydrology (NZ),* **50,** 205-225.

Tsai, T.L. & Yang. J.C. (2006). Modelling of rainfall-triggered shallow landslides. *Envrionmental Geology,* **5,** 525-534.

Vonnote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. & Cushing, C.E. (1980). The River Continuum Concept. *Canadian Fish and Aquatic Society,* **37,** 130-137.

Wilmshurst, J.M. (1997). The impact of human settlement on vegetation and soil stability in Hawke's Bay, New Zealand. *New Zealand Journal of Botany.* **35,** 91-111.

Wolman, M.G. & Miller, J.P. (1960). Magnitude and Frequency of forces in Geomorphic Processes. *The Journal of Geology,* **68,** 54-74.

Ziemer, R.R. (1981). The role of vegetation in the stability of forested slopes. In *Proc. First Union of For. Res. Org., Div. I, XVII World Congress, Kyoto, Japan,* 297-308.

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