# Shallow landslides and vegetation at the catchment scale: a perspective

Chris Phillips[a], Tristram Hales[b], Hugh Smith[c], Les Basher[d]

[a] Manaaki Whenua – Landcare Research, Lincoln 7640, New Zealand. phillipsc@landcareresearch.co.nz

[b] Sustainable Places Research Institute, Cardiff University, 33 Park Place, Cardiff, Wales, UK

[c] Manaaki Whenua – Landcare Research, Riddet Road, Massey University, Palmerston North 4472, New Zealand

[d] EroSed Services, 47B Green Street, Nelson 7011, New Zealand.

## Highlights

- Catchment-scale root reinforcement model development has a way to go before models become useful for catchment and land managers wanting to target areas of shallow landslide susceptibility.
- Understanding how shallow landslides contribute to river sediment loads remains a scaling and connectivity challenge.
- Quantifying mass wasting (including landslide) and sediment interactions in river channels presents different temporal and spatial challenges and must be assessed at the catchment scale.

## Abstract

Shallow, rainfall-triggered landslides are an important catchment process that affect the rate and calibre of sediment within river networks and create a significant hazard, particularly when shallow landslides transform into rapidly moving debris flows. Forests and trees modify the magnitude and rate of shallow landsliding and have been used by land managers for centuries to mitigate their effects. We understand that at the tree and slope scale root reinforcement provides a significant role in stabilising slopes, but at the catchment scale root reinforcement models only partially explain where shallow landslides are likely to occur due to the complexity of subsurface material properties and hydrology. The challenge of scaling from slopes to catchments (from 1-D to 2-D) reflects the scale gap between geomorphic process understanding and modelling, and temporal evolution of material properties. Hence, our understanding does not, as yet, provide the necessary tools to allow vegetation to be targeted most effectively for landslide reduction. This paper aims to provide a perspective on the science underpinning the challenges land and catchment managers face in trying to reduce shallow landslide hazard, manage catchment

sediment budgets, and develop tools for catchment targeting of vegetation. We use our understanding of rainfall-triggered shallow landslides in New Zealand and how vegetation has been used as a tool to reduce their incidence to demonstrate key points.

## Keywords

shallow landslide; catchment; root reinforcement; sediment

## 1. Introduction

Shallow landslides are natural geomorphic processes that shape the landscape, are important as agents of hillslope and landscape-scale sediment transfer and are also hazards to life and infrastructure (Spiker and Gori, 2003; Milledge et al., 2014; Parker et al., 2016; Sidle and Bogaard, 2016). They occur in steep mountainous and hilly landscapes that are covered in a mantle of regolith (e.g. Glade, 2003; Forbes and Broadhead 2011; Garcia-Ruiz et al., 2017) and are commonly triggered by rainstorms (e.g. Rickli and Graf, 2009) or earthquakes (e.g. Croissant et al., 2019). Such landslides transfer sediment from hillslopes to channels (Benda and Dunne 1997a; Gabet and Dunne, 2003), are a disturbance mechanism for forest ecosystems (Hack and Goodlett, 1960), and develop catchment topography (Stock and Dietrich 2003). Additionally, shallow landslides affect humans by rapidly changing the volume of sediment in channels and impacting river water quality, creating hazards to infrastructure and human lives, and loss of soil[1] resulting in declining productivity of grasslands (Rosser and Ross, 2011) and forests (Heaphy et al., 2014).

Like most environmental phenomena, slope instability encompasses a complex set of processes, of which a small subset is usually capable of explaining most of the observed pattern of events (Collison and Griffiths, 2004). Rainfall-triggered shallow landslides commonly occur on steep slopes. They can be triggered by heavy rainfall of either short duration with high rainfall intensity, or long duration with lower intensity (e.g. Guzetti et al., 2004). The initiation of shallow landslides depends on the complex interactions between the physical properties and availability of the regolith, climate, vegetation, land use, hillslope hydrology, and below-ground ecologic processes (Wu, 1995; Rickli and Graf, 2009).

[1] We define a shallow landslide as any landslide that occurs within the material that forms above the bedrock including soil, saprolite, and colluvium. To provide a consistent nomenclature, we will define this material as regolith, noting that this includes much of the mobile component of the regolith in many cases (Anderson et al., 2012). Where we use the term soil, it is to denote the agriculturally productive component of the regolith.

Attempts to characterise the rainfall thresholds necessary to trigger shallow landslides also suggest high variability (Caine, 1980; Guzzetti et al., 2007; Segoni et al., 2018).

Shallow landslides are the most common type of slope failure in many countries such as New Zealand, accounting for 90% of all landslides (Crozier, 2005; Glade, 2003; Fuller et al., 2016). In general terms, shallow landslides typically are complex slide-flow landslides (Hungr et al., 2014). These failures are characterised by a pre-defined, planar sliding surface at a depth of up to 2.0 m, usually (but not exclusively) reflecting the boundary between regolith and bedrock (Hungr et al., 2014). Many rainfall-triggered landslides are also associated with both historical (Marden et al., 2014) and contemporary forest clearance (e.g. timber harvesting - Phillips et al., 2012; Vergani et al., 2016) or wildfires (Istanbulluoglu et al., 2004). They are both part of natural landscape response to high rainfall events, or landscape evolution over long time periods (Dymond and de Rose, 2011; Cerovski-Darriau et al., 2014; McCoy, 2015; Sidle and Bogaard, 2016) and a response to anthropogenic land use practices (Glade, 2003).

Figure 1 Shallow landslides near Whanganui, New Zealand (Photo Harley Betts)

Across geomorphic timescales ($10^3$-$10^5$ years) vegetation type and its history strongly controls the potential for shallow landsliding by producing regolith through the action of roots, transporting that colluvium through processes such as tree throw (Roering et al., 2010) and by adding stability to a slope through root reinforcement, that provides an effective cohesion to slopes (Hubble et al., 2013). Tree throw controls the rate of sediment transport by soil creep and has a strong control on local topography in many places (Roering et al., 2003, Hurst et al., 2013, Gabet and Mudd 2010; Gabet et al., 2015). When considered within the geomorphic framework, vegetation particularly trees and forests, can help stabilise slopes reducing the incidence of shallow landslides in the short term ($10^1$-$10^3$ years) (Sidle et al., 1985; Phillips and Marden, 2005; Greenway, 1987; Stokes et al., 2014), but in the longer term ($10^3$-$10^5$ years), trees promote a thick regolith that is landslide prone (Gabet and Dunne, 2002; Casadei and Dietrich, 2003; Milledge et al., 2014).

At shorter timescales vegetation is an important agent for stabilising steep, regolith-mantled slopes by reinforcing the regolith with roots (Phillips and Watson, 1994; Gabet and Dunne, 2002; Montgomery et al., 2000) and, to a smaller extent, by modifying soil moisture and subsurface hydrology through transpiration, canopy interception, redistribution of rain water, and development of preferential flow paths via live and dead root systems (Hwang et al., 2015; Gonzalez-Ollauri and Mickovski 2017). However, during extreme rain events, forest cover may have a reduced effect on reducing the frequency of landslides whose failure plane is well below the majority of the rooted regolith (Forbes and Broadhead, 2013). Natural (e.g. fire) or human driven (e.g. logging) removal of woody vegetation has been shown to lead to an increase in shallow landslide activity (e.g. O'Loughlin and Pearce, 1976; Montgomery et al., 2000; Roering and Gerber, 2005; Sidle, 1992).

The need to place trees and forests strategically within catchments or watersheds to limit shallow landslides and their impacts while continuing to remain a challenge, has sparked several approaches over the last half century to understand:

1. shallow landslide susceptibility (e.g. Schmidt et al., 2001; van Westen et al., 2008; Reichenbach et al., 2018),
2. landslide triggering thresholds (e.g. Guzzetti et al., 2004, 2008; Segoni et al., 2018),
3. effects of both trees and forests on landslide frequency and severity (e.g. Phillips and Marden 2005; Schmaltz et al., 2017; Guo et al., 2019),
4. models including spatially-explicit landslide and sediment budget models (e.g. von Ruette et al., 2011, 2013; Cislaghi and Bischetti, 2019), and
5. management guidelines (e.g. Swanston, 1985; Chatwin et al., 1994; Jordan, 2002) or tools (e.g. Dymond et al., 2006; Schwab and Geertsema, 2010; Dorren and Schwarz, 2016).

In this article, we examine how vegetation management can affect the frequency and magnitude of shallow landslides at a catchment scale. Where appropriate, we use our understanding of shallow landslides in New Zealand to demonstrate key points; this being more familiar to the authors. We organise the paper into three parts. The first reviews the now classical model of how vegetation provides stability to catchments through hydrologic and root reinforcement effects (e.g. O'Loughlin 1974, 2005; Greenway, 1987; Sidle and Ochiai, 2006; Schwarz et al., 2010, 2013; Stokes et al., 2014) and consider the challenges of uncertainties and land use histories on catchment slope stability. Secondly, we consider landslide susceptibility and hazard under differing vegetation conditions (Guzzetti et al. 2005). We note progress towards landslide hazard predictions that allow spatially explicit calculations of individual landslide probabilities and the challenges of how and where planting vegetation might change these probabilities and understanding how the frequency and magnitude of rainstorms and landslide events might be changing through time. Finally, we consider vegetation and the management of catchments, including the difficulty of obtaining reliable measurements of subsurface properties that reflect their spatial variability at a catchment scale. This remains a significant challenge when trying to integrate geomorphic processes to produce effective management tools.

## 2. Vegetation and landslide triggering at the catchment scale

Rainfall-triggered shallow landslides are episodic events that can impact catchments in various ways depending on their magnitude, extent, and timing. Understanding the factors that control rates of landsliding and sediment delivery is important for assessing the environmental risks associated with such events and for predicting the impacts of land use on erosion (Benda and Dunne, 1997a, 1997b; Gabet and Dunne, 2003; Rengers et al., 2016; McGuire et al., 2016). Landslides cause a stochastic delivery of sediment to the upper parts of mountain catchments, with the frequency of landsliding being directly related to the types of vegetation and their potential losses due to natural (e.g. wildfires) or anthropogenic activities (e.g. logging) (e.g. Sidle et al., 1985). Catastrophic landslide events are often linked to extreme rainfall events together with vegetation disturbance. There is a strong causal link between the relative rates of root decay and regeneration and the timing of landsliding activity via a mechanical reinforcement that has been observed in many places (e.g. Wu et al., 1979; O'Loughlin and Watson, 1979; Schmidt et al., 2001).

Vegetation plays an additional role in affecting the hydrology that governs shallow landslide triggering. Landslides are triggered by the development of pore pressures from vertically directed infiltration from intense rainfall, convergent throughflow and/or exfiltration from shallow groundwater systems (Iverson, 2000; Montgomery et al., 1997). The result of complex hillslope hydrology is that while most shallow landslides trigger within convergent topography, where throughflow is important (Dietrich et al., 2007), they are not exclusively triggered in these areas (Fig. 1). Additionally, there are local effects on stability caused by the additional mass of the vegetation (called the surcharge) and through perturbations of hydrology caused by interception, transpiration, and changes to the structure of the regolith by the addition of leaf litter and through roots creating macropores (Ghestem et al., 2011; Keim and Skaugset, 2003).

Numerous approaches have been taken to model landslide initiation at a catchment scale, including empirical models based solely on rainfall characteristics to more physically-based landslide models in which stability is assessed using the limit equilibrium method and expressed in terms of factor of safety analysis (FoS) (e.g. Sidle, 1992; Collison and Griffiths, 2004). Distributed, physically-based landslide models have become more prevalent with improvements in advanced GIS and DEM technology which is allowing the prediction of landslides at the catchment or regional scale (Montgomery and Dietrich, 1994). These sometimes couple ecohydrologic models to estimate subsurface vegetation parameters like rooting depth (Sivandran and Bras, 2013). However, the limiting factor for most of these models is the sparse data available for the input parameters, many of which are not available at the scales at which the models can now be applied. This is starting to be addressed with probabilistic models that use dynamic parameters to deal with the lack of data and uncertainty (e.g. van Zadelhoff et al., 2021).

Physically-based modelling of shallow landslide potential, regardless of model complexity, relies on the limit equilibrium method introduced by Mohr-Coulomb. The most common application of this method assumes an infinite slope (e.g. Montgomery and Dietrich, 1994; Pack et al., 2001; Baum et al., 2008). The limit equilibrium method considers the landslide potential to reflect the balance of colluvium shear force and strength. In its simplest, 1-dimensional form this balance is reflected as a factor of safety (FoS)

$$FoS = \frac{c' + (\gamma z cos^2\beta - u) tan\phi'}{\gamma z sin\beta cos\beta},$$

with $c'$ representing the effective cohesion, $\gamma$ is the unit weight of colluvium, z is colluvium depth, $\beta$ is the slope angle, u is the pore pressure, and $\phi'$is the effective friction angle. The addition of plant roots, which reinforce the regolith mostly via the friction between the root's surface and the regolith (e.g. Schwarz et al., 2010; Vergani et al., 2017; Cohen and Schwarz, 2017), provides additional shear strength in excess of that provided by the internal friction of the colluvium, hence is considered as a component of the effective cohesion. Vegetation affects all of the terms in this equation (even slope angle, e.g.

Roering et al., 2003, 2010; Hurst et al., 2013) at geomorphic timescales, such that we would expect a system that has not been perturbed by land use or climate change, to reach an equilibrium in terms of the rate of sediment discharged from hillslopes by shallow landslides and creep processes and that generated by soil production mechanisms such as tree throw (Dietrich and Dunne, 1978). At shorter, management timescales, the three terms that are most influential on catchment-scale slope stability are the effective cohesion, regolith thickness, and pore pressure (D'Odorico and Fagherazzi, 2003). Possibly the most important, and poorly understood relationship is that between the effective cohesion and the regolith thickness that can be maintained. The magnitude of this additional effective cohesion has been discussed with models evolving over many decades from relatively simple approaches (Wu et al., 1979) to more complex models where root reinforcement is assessed across scales from a single root to a tree root system to a stand of trees (Schwarz et al., 2010; Schwarz et al., 2013, 2014; Hales, 2018), to physically based distributed models as outlined above (e.g. Hwang et al., 2015) and those that are designed to assist practitioners (Dhakal and Sidle, 2003; Schwarz et al., 2014, 2016; Dazio et al., 2018; Bischetti and Chiaradia, 2010; Chiaradia et al., 2012; Cislaghi and Bishchetti, 2019).

The addition of effective cohesion, such as that provided by plant roots, creates a regolith depth dependence on failure that is higher than that provided by earth pressure in cohesionless regolith Milledge et al., 2014). The importance of this dependence can be illustrated by plotting the minimum regolith depth and slope angle under hydrostatic pore pressure conditions (Crozier et al., 1990; D'Odorico and Fagherazzi, 2003; Parker et al., 2016) (Figure 2). Locally, tree roots generate effective cohesion values of up to 50 kPA (Schmidt et al., 2001), such that a landscape occupied by forest will contain stable colluvium with thicknesses of >1 m, under most pore pressure conditions. However, rapid changes in vegetation type, particularly the conversion of forest to other land use types, can dramatically lower the effective cohesion and make slopes considerably more unstable. Additionally, the relationship between cohesion, and colluvium depth may affect the catchment response to long-term climate-driven changes in precipitation, such that the relatively slow recovery of regolith thickness after a shallow landslide provides a stronger constraint on landslide potential than changes in landslide frequency (Parker et al., 2016.) This work demonstrates a stronger need for effective methods for understanding the subsurface structure of catchments to improve their management (Brantley et al., 2017).

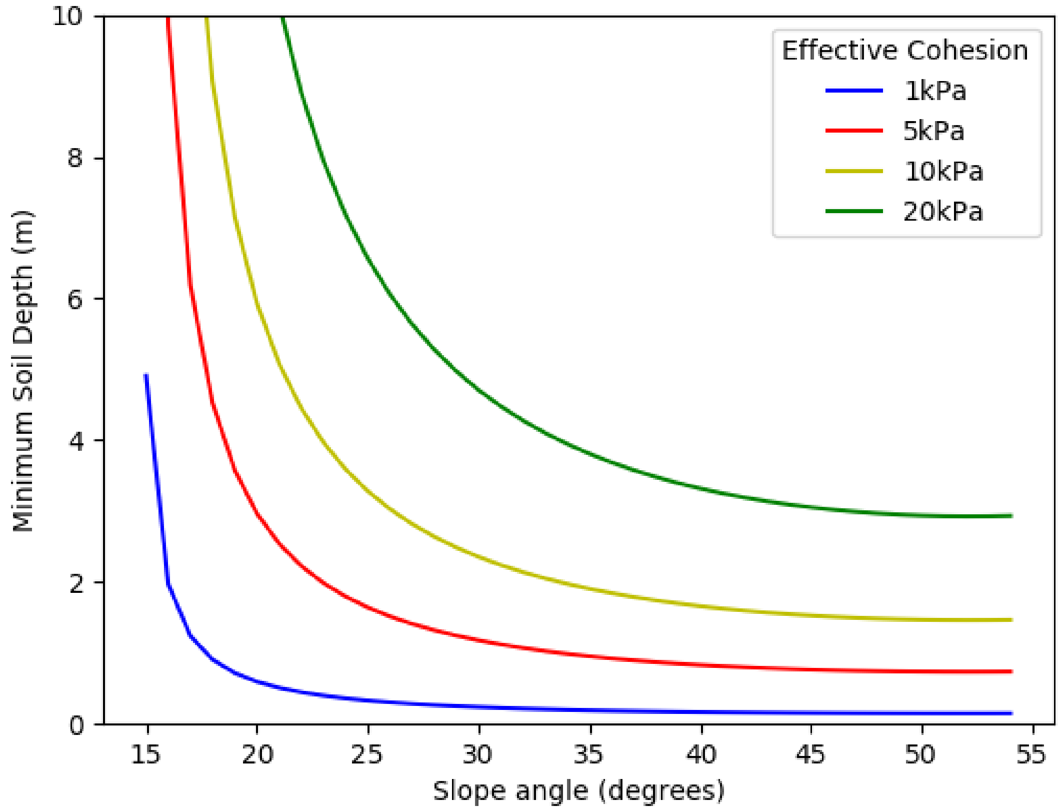


Figure 2 Analytical solutions of the maximum stable regolith depth for hydrostatic pore pressures under different effective cohesion values. These solutions show the striking role that cohesion, which in hillslope regolith is often dominated by root reinforcement, has on stabilising slopes. Similarly, it highlights how even small losses and gains in effective cohesion could cause dramatic changes to the stability of a slope. In this example, friction angle is 30 degrees, unit weight of soil is 17,600 N/m$^3$.

Recent advances in our process-based understanding of the role of vegetation and physical constraints such as earth pressure has improved our understanding of the controls on shallow landslide size and depth (Milledge et al, 2014). Better process understanding, combined with efficient methods for analysing clusters of unstable cells that can estimate landslide size (Bellugi et al, 2015). Prediction of locations of landslides within a particular rainstorm event remains challenging, highlighting issues of parameterisation, calibration, and verification, and computation intensity. Parameterising subsurface mechanical and hydraulic properties in mountainous terrain remains a significant challenge, particularly because of the heterogeneity of these properties across these landscapes, the lack of systematic empirical measurement of these parameters for slopes, and poor understanding of the statistical distribution of properties at this scale (Burton and Bathurst 1998). These issues of parameterisation mean that calibration of models is often best done using the historical landslide record. The quality of the parameterisation (and verification) of these models depends on the completeness and length of the record.

Stochastic modelling of shallow landslides at a catchment scale has provided an opportunity to test our understanding of how landslide frequency and magnitude and resulting sediment fluxes respond to naturally variable rainfall and disturbance. The competition between the recovery of soil depths at millennial timescales and the stochastic rainfall and fire events that recur at decadal to centennial timescale sets the spatial pattern and magnitude of shallow landslide events (Parker et al., 2016; Benda and Dunne, 1997a). These studies show that the number of potential failure sites, and thus the long-term frequency of landsliding was set by the rate of soil depth recovery. The relationship between the antecedent effects of fire, which reduces root strength, and rainfall governed the magnitude and location of individual landsliding events (Benda and Dunne, 1997a). When the sediment generated by these events was routed through catchments by stochastic flooding events, large changes to bed topography (on a scale of metres) were created in lower order channels but were barely detectable in 5$^{th}$ order catchments (Benda and Dunne, 1997b). Istanbulluoglu et al., (2004) modelled how changes in forest stand density and productivity conditions (manifested by different root cohesion values) influence the magnitude and frequency of sediment delivery from gully erosion, shallow landsliding and debris flows. Their simulation results reproduced long-term (10,000 year) average sediment yields. When the model was perturbed by wildfires, rapid reduction in root cohesion caused a more intense sedimentary response than forest harvesting. Sediment fluxes were dominated by episodic events whose timing was controlled by vegetation root cohesion and density (Istanbulluoglu et al., 2004). This work demonstrated the stochastic nature of the extreme precipitation and deforestation events that drive landslide events, while also noting that there is an averaging effect of both the sediment signal of landsliding downstream and through time.  Hence, reconciling long-term average sediment yields versus short-term stream sediment fluxes is difficult due to the relatively short nature of the observational record, and the unreliable nature of the sedimentary records of the upper parts of catchments.

Where sediment yields have been compared across timescales, we have observed both an increase and decrease in short-term sediment yield relative to the long term. For example, Kirchner et al., (2001) found that long-term erosion rates over 10,000-year time scales when compared to short-term measurements (10–84 years) produced sediment yields on average 17 times higher than the short-term stream sediment fluxes. The authors concluded that this significant difference suggests that sediment delivery from mountain watersheds is extremely episodic, and that long-term sediment delivery is dominated by catastrophic rare events (Kirchner et al., 2001). Hence, lower order streams that are prone to landsliding can expect large, rapid changes in bed elevation at the annual to decadal timescale over which catchment managers are interested. Where catchment-scale landscape evolutions models have included short-term disturbances to vegetation, there is a commensurate, short-term increase in sediment yields (Istanbulluoglu et al., 2004, Guthrie, 2009). These studies highlight that land use change such as due to forest harvesting may have a greater impact on catchment sediment budgets than climate change. At small catchment and storm event scales, comparisons of sediment yield under different vegetation cover, and studies of the impact of deforestation, show that forested catchments yield 50–80% less sediment than pasture catchments (e.g. Hicks, 1990; Fahey et al., 2003) and can have a mean annual sediment yield up to 95% less than pasture catchments (Hicks, 1990).

Historical sediment records within the well-studied Waipaoa River catchment in New Zealand have provided important observational evidence of the role of reforestation on landsliding driven sediment yields. Reid and Page (2002) analysed the effectiveness of reforestation in reducing landslide contribution to sediment load of the Waipaoa River catchment. They suggested that shallow landslides contribute about 15+/-5% of the suspended sediment load in the river and that 75% of the sediment production from the landslides occurs during storms with recurrence intervals of less than 27 years. They also suggested reforestation between 1960 and 1995 had produced a 10% decrease in sediment from landslides but had only reduced total sediment load by 2%. If the most susceptible areas in the catchment were targeted, the sediment generation rate from landsliding could be reduced by 40% but it would result in only a 6% reduction in the sediment load of the Waipaoa because of the importance of gully and streambank erosion in this catchment (Hicks et al., 2000). Marden (2012) argued that reforestation with exotic pines in the erosion-prone East Coast region of New Zealand successfully stabilised existing erosion forms and prevented the initiation of new ones. Using modelled reforestation scenarios, he indicated that sediment generation from earthflows and shallow landslides would be negligible within 8-10 years of planting. Marden et al., (2014) quantified the effectiveness of exotic reforestation as an erosion control strategy on both sediment generation in the headwaters of the Waipaoa River in New Zealand and on downstream sediment yield over the period 1939–1988. Additionally, studies of landslides during large storm events in New Zealand show the effect of localised erosion control by vegetation on the sediment delivery ratio (SDR) in a whole farm context is typically low, i.e., the amount of sediment delivered to the rivers and transported to the catchment outlet is a small proportion of the total mass that failed (e.g. Page et al., 1994, 1999; Preston 2008) and even lower when multiple landslide events are considered (Jones and Preston, 2012). This implies that the impacts of vegetation on landslide contribution to sediment yield are likely to be buffered by temporary sediment storage in the landscape resulting in less direct influence on sediment yield than on hillslope erosion rates. By contrast, erosion from gullying processes is often well connected to the stream network and most sediment eroded is delivered to the stream network (SDR is close to 1).

The improvements of physical understanding of shallow landslide processes across temporal and spatial scales, has improved our ability to predict the magnitudes and frequencies of potential landslide events, yet reliably predicting the location of individual landslides remains elusive. Increasingly complex and dynamic models of shallow landslide susceptibility have moved beyond the static approach by applying spatially and temporally varying distributions of vegetation, colluvium, and hydrologic properties. Yet computational complexity remains a challenge, as does parameterisation. Additionally, we do not have a strong theoretical or practical basis for including temporal changes in vegetation properties due to disturbances such as fire and disease, or how to account for different stages in vegetation growth or density (e.g. Flepp et al. 2021). Similarly, our understanding of the spatial distribution of regolith depth is extremely limited, with our best estimates coming from manual excavation and soil tile probe methods (Reneau et al., 1990; de Rose et al., 1991; Hales et al., 2009; Parker et al., 2016; Gabet et al., 2015). Despite advances in shallow geophysical methods for estimating colluvium depths associated with Critical Zone Observatories, there remain practical issues of their application in steep catchments (Befus et al., 2011; Pazzi et al., 2017). In landscapes with frequent rainfall, the temporal distribution of colluvium thickness may limit the rates of shallow landslide triggering (Benda and Dunne 1997a; Gabet and Dunne, 2003; Parker et al., 2016), although few studies have attempted to understand these dynamics. In particular, landslide events themselves can change the susceptibility of the terrain to future events, commonly by removing susceptible material and thereby increasing the resistance of the terrain (Crozier and Preston, 1999).

## 3. Landslide modelling to estimate susceptibility and hazard

Calculating landslide susceptibility and hazard at the catchment scale under varying vegetation conditions has been a core challenge for many decades. Given the complexity of the processes governing the frequency and magnitude of shallow landsliding and aleatoric and epistemic uncertainties in parameters, a range of different approaches have been implemented to this challenge. Landslide susceptibility is the likelihood of a landslide occurring in an area depending on local terrain conditions i.e., estimating where landslides are likely to occur (Guzzetti et al., 2005). By definition, landslide susceptibility is a non-temporal concept that refers to locations where landslides preferentially occur based on an understanding of the topographic, hydrologic, and material properties that act as contributory factors. The factors that control landslide susceptibility are topographic (slope steepness, elevation/relative relief, aspect, slope shape/curvature), geologic (lithology, strength of bedrock and regolith), vegetation cover or land use, climate (annual rainfall, rainfall intensity and duration) and presence of roads and infrastructure. Of these factors slope, geology/lithology and rainfall are the most important and different combinations of these factors are used in the various assessments of susceptibility (e.g. Minder et al., 2009; Smith et al., 2021). In both the literature and common usage, confusion exists between landslide susceptibility and landslide hazard and the terms are often used as synonyms despite the words expressing different concepts (Reichenbach et al., 2018). Landslide hazard is the probability that a landslide of a given magnitude will occur in a given period and in a given area. In addition to predicting where a slope failure will occur, landslide hazard predicts how frequently it will occur, and how large it will be (Guzzetti et al., 2005).

Landslide susceptibility assessment emerged in the mid-1970s and there have been many papers published since using a variety of approaches and methods in different geological and climatic settings (see Reichenbach et al., 2018). All approaches are based upon a few assumptions: (1) that landslides can be recognised, classified, and mapped in the field or by analysing remotely-sensed imagery; (2) landslides and their occurrence are controlled by physical laws that can be analysed empirically, statistically, or deterministically; (3) for statistical landslide susceptibility modelling, the past and present distribution of landslides reflects the future distribution of landslides; (4) spatial landslide occurrence can be inferred from heuristic knowledge, computed through the analysis of environmental information, or predicted using physical models. Many of the parameters that form the basis of our understanding of slope stability, such as friction or cohesion, have an aleatoric uncertainty. However, it is the epistemic uncertainty associated with the history of landsliding, past changes to boundary conditions through land use or climate changes, and parameters such as regolith thickness and pore pressure distributions that provide the greatest limitation on our ability to develop predictive tools that might be useful for land managers. Landslide susceptibility model performance is often assessed using a receiver operating characteristic (ROC) curve, which plots the true positive rate against the false positive rate. Measuring the area under a ROC is commonly used as an estimate of model performance. High ROC values of up to 90% (e.g. Smith et al., 2021) highlight the efficiency of many landslide susceptibility methods.

Approaches and methods for assigning landslide susceptibility can be qualitative or quantitative, and direct or indirect. Qualitative approaches are subjective, ascertain susceptibility heuristically, and portray susceptibility levels using descriptive (qualitative) terms. Quantitative methods produce numerical estimates; in other words, probabilities of occurrence of landslide phenomena in any susceptibility zone (Guzzetti et al., 1999). These include geomorphological mapping (Cardinali et al., 2002), analysis of landslide inventories, heuristic terrain and stability zoning (van Westen et al., 1997; Guzzetti et al., 1999), physically-based models (Montgomery and Dietrich, 1994; van Asch et al., 2007; Alvioli and Baum, 2016) and statistically-based classification methods (Guzzetti et al., 1999; van Westen et al., 2008). The development of satellite technologies to develop better landslide inventories has proven to be an essential tool to improve the quality of the empirical basis required for better modelling of catchment landsliding. Data from such inventories is necessary to help develop, calibrate and validate both aspatial and spatially-distributed conceptual, physical and statistical models (e.g. Casadei et al., 2003; Blahut et al., 2010; Van den Eeckhaut et al., 2011, 2012; Guzzetti et al., 2006; Marc et al., 2015).

### 3.1 Landslide inventories

The collection of data following a shallow-landslide event serves several purposes including:

**1.** determining the geographic extent of “damage”, i.e., which catchments are most affected (Page et al., 1999; Dymond et al., 2006),

**2.** understanding the triggering mechanisms and factors that contributed to slope failure (Petschko et al., 2013; Zieher et al., 2016),

**3.** assessing connectivity to stream networks and delivery of sediment and the contribution of landslides to catchment sediment loads/budgets (Trustrum et al., 1999), and

**4.** assessment of the on-site and downstream impacts (including economic costs) (Phillips and Marden, 2005; Dominati et al., 2014).

Until the rapid expansion of high-quality satellite imagery over the past decade, our understanding of the spatial distribution of shallow landsliding was largely limited to a few meticulously collected datasets or inventories of landslides and rainfall often focused on catchments or sub-regions of interest obtained from aerial imagery (e.g. Marden and Rowan, 1993; Malamud et al., 2004). Multi-temporal inventories generally of smaller areas, were also created from repeated historic aerial imagery (Betts et al., 2017). However, the increase in the frequency of satellite imagery has complemented these efforts by largely improving the capture of where landslides occur, particularly for shallow landslides that are too small to accurately map from lower-resolution imagery.

Landslide inventories have allowed an understanding of both the size and frequency of individual landslides, as well as the size and frequency of landslide events where a single rainstorm may trigger hundreds or thousands of shallow landslides (e.g. Cyclone Bola, New Zealand (Hicks, 1991; Marden and Rowan, 1993); Hurricanes Francis and Ivan, North Carolina (Wooten et al., 2016)). Multi-temporal landslide inventories have also been extremely important for understanding post-earthquake landsliding (Fan et al., 2019; Marc et al., 2015) and increasingly for understanding the patterns of rainfall-triggered shallow landsliding (Chen et al., 2016). Increasingly frequent landslide inventories allow a better understanding of the controls on event magnitude and frequency, and path dependencies (Samia et al., 2017). However, multi-temporal landslide inventories in forested terrain, unlike for non-forested landscapes, are scarce (Schmaltz et al., 2017). This results in difficulties in establishing empirical relationships between shallow landslides and forest/tree cover (density, age, species, etc), especially at the landscape and catchment scale. Forests have variations in vegetation species and age which influences the variability of root cohesion which can then dominate the local stability of landslide-initiation sites (Schmidt et al., 2001).

Aerial photo interpretation, and many remote sensing approaches have difficulty in detecting small landslides under or within vegetation and the portion of visually non-detected landslides in rugged forested areas can sum up to 85% of the total number of landslides (Brardinoni et al., 2003). In many inventories of rainfall triggered landslides that compare landscape response for different land covers or land uses, forests or woodlands generally have much lower landslide densities. For example, in New Zealand following several regional landslide events, forested landscapes have been reported as having fewer landslides and lower landslide densities compared to grass covered slopes (Phillips et al., 1991; Marden and Rowan, 1993; Bergin et al., 1995; Rosser et al., 2019). In many places the occurrence of significant landslide events is well known with observations and data relating to these events built up over decades (Rosser et al., 2017; Zieher et al., 2016; Chen et al., 2015). In other areas however, particularly those more remote or less densely populated, records do not exist, though the impacts may be no less severe. Many landslide events can also affect relatively small areas (<10 $km^2$) within larger catchments being triggered by cells of high or intense rainfall while others are more regional in extent (often related to extensive flooding) affecting much larger areas and producing thousands of landslides. These have been called multiple-occurrence regional landslide events (MORLEs – Crozier, 2005, 2017).

### 3.2 Modelling landslide susceptibility and hazard under differing vegetation

As technology and computing power have progressed, so have advances in how landslide susceptibility is assessed. Reichenbach et al. (2018) reviewed statistically-based approaches for landslide susceptibility modelling and associated terrain zonation and suggested that physically- and statistically-based methods are preferred to determine landslide susceptibility in quantitative terms. One of the earliest investigations analysed published data from 73 worldwide examples where rainfall intensity and duration had been measured in association with the triggering of shallow landslides to develop a minimum rainfall intensity-duration threshold for debris flows (Caine, 1980). The concept of rainfall thresholds as presented by Caine (1980) built upon earlier recognition by Campbell (1975) of the relationship of high intensity rainfall in the triggering of shallow landslides and by Starkel (1979) who theorized a critical rainfall which was a combination of rainfall intensity and duration.

Subsequent work has continued to refine thresholds for differing geological settings using a mix of approaches (e.g. Wilson and Wieczorek, 1995; Glade 1998; Wieczorek and Guzzetti, 2000; Guzzetti et al., 2007; Frattini et al., 2009; Salciarini et al., 2012; Nikolopoulos et al., 2014; Palladino et al., 2018; Peruccacci et al., 2017; Segoni et al., 2018). Many of these approaches are now focussed on providing support for the development of regional landslide early warning systems (e.g. Gariano et al., 2018). Choice of parameter inputs is a key challenge for landslide susceptibility analysis, particularly geological inputs which may be more accurate when lithology is combined with other geological information (Segoni et al., 2020). There is also some general agreement that whatever approach is used to determine susceptibility, fewer classes seem to perform better than having many, i.e., adding additional parameters to susceptibility models often doesn't improve their predictive performance. A particularly challenging assumption that has only been tested in a small number of cases is the issue of path dependency, i.e., if a landslide fails in one location, is the probability of a similar failure in the same location changed (Parker et al., 2016; Samia et al., 2017). While there are observations of repeated landslide triggering, the thinning of regolith associated with shallow landslides will certainly change the probability distribution of failure at that location, creating an epistemic uncertainty leading to what has been termed terrain resistance (Crozier and Preston 1999) or exhaustion.

Statistical landslide hazard models are developed by analysing the distribution of landslides with respect to topographic, geologic and hydrologic parameters. These models develop a probability of a landslide event anywhere within a spatial area (e.g. a catchment), for a given rainfall event that is usually expressed as a combined intensity (maximum rainfall rate) and duration (a time) (e.g. Malamud et al., 2004; Guzzetti et al., 2006). These models are used globally and represent the simplest method for determining an estimate of landslide hazard and are particularly useful where the hazard estimate does not depend on spatial parameters. For example, when estimating debris flow hazard at the mouth of a catchment, it may not matter where in the catchment the debris flow is sourced, just the probability that it will reach the mouth.  Including the distributions of triggering and non-triggering rainfall events in a Bayesian methodology allows the development of failure probabilities that better reflect uncertainties inherent in shallow landslide systems (Berti et al., 2012). Recently, the use of machine learning has provided a new tool for developing these statistical methods that is versatile, improves through time as more data is added, and may have some promise as a predictive tool (Huang et al., 2020; Liu et al., 2021; Smith et al., 2021).

Spatially-distributed models of landslide triggering are an important process-based tool for estimating landslide susceptibility. These models are typically digital topography-based estimates of landslide susceptibility, with a factor of safety calculated for each individual pixel. These models include a topography-based hydrological model that varies in its form. Such models include SHALSTAB (Montgomery et al., 1994), dSLAM (Wu and Sidle 1995), TRIGRS (Baum et al., 2008), SINMAP (Pack et al., 2001), HIRESS (Rossi et al., 2013; Salvatici et al., 2018) as well as many others (e.g. Chang and Chiang, 2009). However, the ability of physically-based models for shallow landslide hazard analysis has been questioned (Zieher et al., 2017) but the approach is considered feasible for computing a regional overview of slope stability and may oversimplify at the local scale, where slope-based geotechnical modelling may prove more fruitful. Increasingly the quality of the hydrological and geomorphic modelling underpinning these models has improved considerably (Anagnostopoulos et al., 2015; Lehmann and Or, 2012; Tang et al., 2019; Thomas et al., 2021; Von Ruette et al., 2013).

Process-based shallow landslide hazard models are less common. While slope scale landslide hazard analysis is a common geotechnical method that is applied to numerous slopes globally (a summary of these methods is outside the scope of this article), there are few examples of the application of slope-scale analysis to the shallow landslide problem. In particular, simplified slope-scale analysis of shallow landsliding has been applied effectively as a tool for disaster relief and mitigation particularly to support the risk assessment of infrastructure (CHASM; Thiebes et al., 2014). The applications of these models can be made increasingly flexible through the use of search algorithms to determine the most likely failure planes which makes them important tools for decision support at the slope scale (Bozzolan et al., 2020).

## 4. Vegetation for managing catchments

Vegetation, particularly trees and forests, is widely used as a catchment management tool. It can: regulate water quality and quantity; the amount of carbon sequestration; provide an alternative income source for poor/marginal agricultural land; assist with managing biodiversity and other ecological goals; and can change catchment sediment yields based on the characteristics and extent of forest cover (Phillips and Marden, 2005; Hicks et al., 2000; Marden et al., 2014).

In many catchments, a wide range of topographic conditions and land uses occur, and tools are required by land or catchment managers to target mitigation of soil erosion, including that caused by shallow landslides, to reduce sediment loads in rivers to meet regulatory standards (Dymond et al., 2010; Dymond et al., 2016; Betts et al., 2017; EU water framework directive, 2000; Bathurst et al., 2005; Elliott and Basher, 2011). Given that forests are a multi-functional tool for catchment management, the lack of clarity on the trade-offs associated with the management of forest catchments for different purposes (Beland Lindahl et al., 2013) has as yet poorly understood consequences for mitigating landslides and other hazards.

Management of landscape susceptibility to rainfall triggered landslides with vegetation is typically applied at two broad geographic scales: 1) individual slopes within a sub-catchment, and 2) upland landscapes ranging in size from sub-catchments to entire river basins (Forbes and Broadhead, 2011; Bathurst et al., 2010). At the individual slope level, the focus of most investigations to date has been on either small-scale hydro-mechanical contribution of vegetation to stabilising the regolith or assessing failures once they occur to determine details of triggering mechanism. At the landscape level, forest related options include retention, rehabilitation or restoration of forests. However, at the catchment scale, the issues are more complex particularly in relation to the interaction between hillslope stability and channel stability (e.g. Benda 1990; Benda and Dunne, 1997a). For example, determining where in a catchment and how much forest or many trees are needed to reduce future landslide occurrence and thus reduce catchment sediment loads is a problem that has largely not been addressed other than via modelling (e.g. Bathurst et al., 2010; Bovolo and Bathurst, 2012). Because landslides do not normally occur uniformly across a catchment, it has been suggested that careful targeting of forests and trees could produce a disproportionately large reduction in landslide occurrence and sediment yield (e.g. Reid and Page, 2002). In countries such as New Zealand where the susceptibility to shallow landslides is high in many places, the management response has been to blanket afforest or reforest whole catchments (e.g. Phillips and Marden, 2005; Phillips et al., 2013) rather than consider and target the specific parts of catchments that need treating. The exception has been where retention of pastoral agriculture in landslide susceptible areas has required space-planted trees to reduce future landslide occurrence (McIvor et al., 2011; Schwarz et al., 2016), though the scale of planting and lack of targeting to the most susceptible areas is inadequate to significantly reduce landslide erosion (Spiekermann et al., 2021).

Our ability to apply simple models across the landscape for practical management purposes at a range of scales is limited, especially in terms of defining/predicting where vegetation could have the most beneficial effect, i.e. targeting to reduce landslide hazard (Gonzalez-Ollauri and Mickovski, 2017). Many tools are based on simplified models that do not satisfactorily represent the main underlying mechanical and hydrological processes involved in the reinforcement of slope stability by vegetation, despite progress in this area (e.g. Tordesillas et al., 2018). For example, most models cannot describe the three dimensional (3D) spatial heterogeneity of vegetation. Nor can these models describe realistic slope geometry as they are two dimensional (2D) (Stokes et al., 2014). And lastly, although several commercial and freely available tools for calculating slope stability exist (e.g. SLOPE/W, PLAXIS, SHALSTAB, TRIGRS) they are generally not able to accurately predict the likelihood of a landslide within a given landscape. Hence, achieving an appropriate scale of modelling for the practitioner remains a balance between parameter heavy spatially-distributed models and simple, but poorly constrained modelling. A focus on simple field-based measures, such as regolith depth mapping (e.g. Parker et al., 2016), may provide important constraints at the management scale.

Catchment-scale modelling tools that link shallow landslide initiation to sediment yield and sediment within rivers are becoming increasingly important for catchment managers who are often responsible for reducing sediment loads in rivers to meet water quality targets and/or reduce the impacts of natural hazards on downstream communities and infrastructure, and on natural habitat including in-stream habitat. Such models aim to represent and include the contribution from all erosion processes and operate at scales useful to management (e.g. Wilkinson et al., 2005, 2008; Betts et al., 2017). They aim to provide long-term (decadal or longer) average sediment contribution from shallow landslides (and other processes) as well as understanding the implications of catchment management on sediment yields (e.g. Dymond et al., 2016).

Burton and Bathurst (1998) developed one of the earliest approaches to assess the contribution of shallow landslide erosion to catchment sediment yield using the model SHETRAN (Ewen, 1995). The approach determines when and where landslides occur in a catchment in response to time-varying rainfall and snowmelt, the volume of material eroded, and the impact on catchment sediment yield.

Using SHETRAN, Bovolo and Bathurst (2011) modelled the contribution of rainfall-triggered shallow landslides to catchment sediment yield as a function of rainfall return periods. The SHETRAN model has also been used to assess the impacts of major landsliding events on basin scale erosion and sediment yield in Spain (Bathurst et al., 2006) and in Italy (Bathurst et al., 2005). Bathurst et al., (2010) explored the potential for reducing the occurrence of shallow landslides through targeted reforestation of critical parts of a river basin using the SHETRAN model and demonstrated that increasing root cohesion from 300 to 1500 Pa caused a two-thirds reduction in the number of landslides and suggested such approaches provide useful information even on the basis of imperfect data availability but cautioned that model output should be interpreted carefully in the light of parameter uncertainty.

Recent advances using LiDAR and remote sensing have improved the spatial resolution at which landslide susceptibility can now be determined and this coupled with high resolution event information from rain radar offers potential to resolving where to target trees within a catchment to achieve the range of outcomes land managers are seeking (e.g. Jacobs et al., 2020; Vandromme et al., 2020). An increasing number of geospatial technologies (e.g. Synthetic Aperture Radar (SAR) (Burrows et al., 2019); optical satellite imagery (Heleno et al., 2016; Bunn et al., 2019; Hölbling et al., 2016) have been applied to map landslides and produce inventories that are needed to develop susceptibility models and for testing/validating prediction models. New satellites and sensor types have increased the spatial (<0.5 m GSD: e.g. Worldview series, GeoEye-1, Pleiades-1a, etc.) and temporal (2-30 m GSD: e.g. PlanetScope, RapidEye, Sentinel-2, Landsat series, etc.) resolution of available imagery at coarser spatial resolutions. High-resolution data is necessary when considering the size of an individual landslide relative to an individual pixel in places such as New Zealand (Smith et al., 2021). Additionally, satellite-based precipitation data and local radar is becoming increasingly more precise for developing hydrologic parameters (e.g. Pan et al., 2010).

Resolving how many trees at what density and their placement in a catchment, together with determining when they become effective for limiting rainfall-triggered shallow landslides, will we suspect, remain a challenge for some time. Advances in modelling the triggering of shallow landsliding under differing vegetations types described above have yet to be readily translated or applied at the catchment scale in management tools. Broadly, there is a lack of detailed information across a wide range of conditions (regolith depth and texture, slope, climate, etc.) and on triggering thresholds for landslides required to underpin hazard assessment and to enable forecasting or scenario modelling at larger catchment scales, though the latter has received some attention (Guzzetti et al., 2007; Segoni et al. 2018). Consequently, many landslide events are treated as broad random occurrences (i.e., a purely stochastic phenomenon (e.g. Vargas-Cuervo et al., 2019) rather than something that can be managed in any targeted way.

### 4.1 Management of forest cover and space planted trees

Managing catchment forest cover is seen as a major nature-based solution for the reduction of landslide hazards. Hence accurately understanding and describing patterns in landslide occurrence across landscapes and how this is mediated by vegetation is essential for improving our predictive ability for management across a range of scales. There are several articles that summarise and review the effects of woody vegetation and forests on slope stability and how forests and trees are used to provide erosion control (e.g. Greenway, 1987; Sidle and Ochiai, 2006; Norris et al., 2008; Stokes et al., 2014; Phillips et al., 2017). There is also a sizeable literature on the effects of different forest management practices, particularly forest removal, on landslide initiation (e.g. Dhakal and Sidle, 2003; Montgomery et al., 2000; Imaizumi et al., 2008; Imaizumi and Sidle, 2012; Preti, 2012; Goetz et al., 2015). Assessments of such effects have been included in landslide inventories and/or are analysed using physically-based slope stability models at the catchment scale.

The observation of larger shallow landslide events coinciding with forest removal highlights the role of root reinforcement in limiting landsliding rates. These events generally correspond to minima in rooting strength following initial root decay and prior to the regeneration or replanting of trees. This has been referred by several authors as the “window of vulnerability” (Sidle and Ochiai, 2006; Phillips et al., 2017). This window of approximately 3 to 20 years after forest clearing coincides with an increase in landslide rate of about 2 to 10-fold compared to undisturbed forests (Sidle and Bogaard, 2016). While there is strong interest in ways to minimize the increased landslide occurrence particularly following forest removal, the re-introduction or maintenance of forest cover is also seen as a possible solution (Lu et al., 2001; Vanacker et al., 2007). For small catchments (up to a few square kilometres), it makes sense to reforest entire basins to reduce shallow landslides and limit other erosion processes, however it may be unreasonable to expect this for large catchments (100s to 1000s of $km^2$) where people rely on the land for other purposes such as farming. The practice of reforesting entire catchments, even relatively large ones, has been a primary mechanism for treating highly erodible land in New Zealand’s East Coast (Phillips and Marden, 2005; Marden, 2012; Phillips et al., 2013).

In New Zealand, space-planted trees are also used in silvopastoral systems to provide a degree of protection from rainfall-triggered shallow landslides on pastoral hillcountry (e.g. McIvor et al., 2011;

Douglas et al., 2011; Spiekermann et al., 2020). Poplars (*Populus spp.*) and willows (*Salix spp*.) are the main species used and they are typically planted between 20 and 200 trees ha$^{-1}$. Their use is balanced between providing enough benefits (reducing extreme temperatures and evapotranspiration, improve regolith properties, reduce erosion) and reducing pasture productivity through competition for soil resources (nutrients and water) (Benavides et al., 2009). There is little information on the effects of space-planted trees on reducing shallow landslides at the catchment scale, i.e., for catchment sediment budgets and landslide hazard reduction. However, space-planted trees are used as part of silvo-pastoral land use systems and as a soil conservation measure in many countries to reduce erosion (Wilkinson, 1999; McIvor et al., 2008, 2011). For example, empirical measurement at slope scales and modelling using detailed root distribution datasets from root-system excavations, suggest that the triggering of shallow landslides on hill country in New Zealand is prevented when 20-30 cm DBH poplar trees are spaced around 13-15 m (Douglas et al., 2011; Schwarz et al., 2016).

In terms of the strategic placement of forests, woodlands, or widely spaced trees to reduce the incidence of landslides, the literature is particularly scant of tools (models, DSS, guidelines) aimed at catchment-scale targeting. While advances in modelling offer a potential solution, they are often limited by availability of parameter data or are designed to work only at limited scales (e.g. Temgoua et al., 2016, 2017). Resolving the question of how many trees are needed, where to place them and their spacing, and determining when they become effective in terms of limiting the incidence of shallow landslides remains a challenge for catchment managers (Stokes et al., 2014). Additionally, the introduction of the concept of nature-based solutions for ecological disaster risk management (Renaud et al., 2016) and changes to land management strategies, such as through rewilding and abandonment (Moreno-de-las-Heras et al., 2019) suggest that there are multiple management pathways to stabilising catchment hillslopes. However, as indicated above, modelling is likely to provide a pathway, particularly as technology allows improved access to data.

To reduce sediment load in rivers (i.e., improve catchment management), the overall ability to predict the impact of landslide events and consequently the development of effective mitigation measures such as targeted tree planting, is limited not only by knowing where the most susceptible areas are but also by the ability to characterise and then predict the travel path, storm centre, and intensity range within the cell structure of extreme weather systems (Crozier, 2017). Technological advances in radar and improvements in forecasting and storm tracking may help in the future (Brunetti et al., 2018). A further issue in understanding landslide risk in many places has been the lack of standardised data from inventories of past landslide events including their triggering rainfalls resulting in a poor understanding of the frequency and magnitude of landslides and their impacts (Glade and Crozier 1996). This is now being addressed by improvements in technology and availability of semi-automated collection of data from post-storm satellite imagery at appropriate scales (e.g. Bellugi et al., 2015; Bunn et al., 2019; Smith et al., 2021) and availability of rain radar data to characterise rainfall patterns (e.g. Chiang and Chang, 2009; Nyman et al., 2015; Destro et al., 2017).

## 5. Challenges for future research

Catchment management of shallow landslides and the role of vegetation in that management remains a significant future challenge. Within this context, organisations and governments have largely embraced nature-based solutions as a low-cost approach to manage hazardous catchments (e.g. UNDRR 2020). Here we have outlined the current state of science for managing catchments with vegetation, yet there are several outstanding challenges for researchers if they are to meet the current and future needs of catchment managers. Many are not just confined to understanding the role of vegetation on rainfall-triggered shallow landslides. These are not limited to but include:

- Improving the spatial and temporal frequency of landslide inventories, including producing 'multi-event' inventories when event landslide densities are high. Landslide inventories remain our most useful tool for estimating and modelling landslide susceptibility and hazard. Shallow landslide events are relatively rare and often occur in remote locations, hence development of better and more frequent landslide inventories, particularly ones that are openly available will improve our ability to understand controls on landslide triggering. The New Zealand setting is well suited to this approach (Smith et al., 2021),
- Understanding the influence of different management approaches, forest types, and tree spacing on landslide susceptibility (Moos et al., 2016). Increasingly new and different approaches to the management of catchments have been proposed, including land abandonment and rewilding, alongside traditional forestry approaches. Each approach will change landslide frequency and magnitude in a different way through time.
- Building models and approaches that can bridge issues of scale in modelling, particularly in data-poor environments (Peeters et al., 2008). The issues of aleatoric and epistemic uncertainty in our current modelling approaches remain a significant limitation to bridging between detailed process modelling approaches and the simplified statistical modelling approaches commonly used in management. This includes developing ways to include the 3D spatial distribution of root

and regolith properties in models with appropriate computation times (Temgoua et al., 2016) and development of realistic root growth models that provide spatial patterns of root distribution or density over time (Tobin et al., 2007; Danjon et al., 2008; Saint Cast et al., 2019),

- Improving understanding of how shallow landslides contribute to river sediment loads. These challenges have been referred to in terms of scale (i.e. how much) and connectivity (i.e. by what pathway) (Sidle et al., 2017). Better understanding of the stochasticity of both the landsliding and fluvial processes are important to tackling this challenge.
- Resolving at what scales and situations (e.g. storm rainfalls) does the “forest effect” on reducing landslide incidence disappear i.e., a magnitude-frequency-scale question. This problem reflects the integration of historical land management and long-term geomorphic processes, in particular estimating the spatio-temporal patterns of root strength, pore pressure, regolith depth and hydraulic properties across the landscape (e.g. Cislaghi et al., 2017; Schmaltz and Mergili, 2018; Hales, 2018; Giadrossich et al., 2020; Masi et al., 2021). These represent the key epistemic uncertainties driven by vegetation and require better understanding how much field data (and generating them) are needed to calibrate and validate existing and future models across a range of realistic management situations, and
- Identifying and meeting the concerns of practitioners/land managers via co-production of guidelines, models, and management tools (Stokes et al., 2014).

## 6. Concluding remarks

In this paper we outlined the role of vegetation for managing shallow landslide occurrence, with a focus on how vegetation is used at the catchment scale and presented a summary of the approaches used to address this issue. While there have been significant improvements, particularly in the development of models and tools to help catchment managers manage both the incidence of rainfall triggered shallow landslides and their impacts on catchment sediment yields, there are still major challenges ahead. Developing appropriate tools to aid specific catchment targeting of vegetation to “treat” the most susceptible parts of the landscape to rainfall-triggered landslides is a pressing need for catchment and land managers. A further need is the availability of field data at the range of scales that are required for parameterising many of the models currently available, particularly at the landscape to regional scales. In part, this limits usefulness of many models for practitioners who are required to manage such catchment hazards or improve catchment water quality to meet regulatory targets.

Thus, in many applied situations, the benefit of modelling greater process complexity is offset by the punitive costs of data collection and by the uncertainty attached to the associated data, often resulting in the application of simple models driven primarily by slope and basic regolith or rock properties or by average values of root cohesion. However, some types of data collection are becoming increasingly affordable (e.g. remote sensing (including LiDAR) can provide cost-effective data collection for landslide inventories and for generating DEMs from which slope information can be obtained), but others remain difficult and expensive particularly where manual methods must still be used (e.g. obtaining tree root distribution and regolith physical properties).

As advances in remote sensing and other sensing technologies improve, there is hope that the paucity of field data needed to improve the development, accuracy and utility of models will cease to be a limiting issue and that practitioners and catchment managers will eventually have simple and robust tools to enable them to manage for, and respond to, rainfall-triggered landslide events. Lastly, they need to be confident that when they target vegetation within catchments to reduce the impacts of such events it will be successful.

## Acknowledgements

The conference organisers of SBEE21 - 5th International Conference on Soil-, Bio- and Eco-Engineering, Zollikofen, Switzerland, June 2021 - invited the first two authors to contribute to the conference. In part, this paper formed a keynote address by the second author. The immediate colleagues of the authors are thanked for useful discussion during the preparation of this manuscript. Raphael Spiekermann reviewed an early draft of this paper and comments from two anonymous reviewers helped shape the final paper. Funding was provided in part by the “Smarter targeting of erosion control” research programme, funded by Ministry of Business, Innovation & Employment, New Zealand, Contract C09X1804 and by Manaaki Whenua – Landcare Research’s internal Strategic Science Investment Fund.

## Competing interests

The authors declare there are no competing interests.

## References

Alvioli M, Baum RL 2016. Parallelization of the TRIGRS model for rainfall-induced landslides using the message passing interface. Environ. Model. Softw. 81, 122–135. https://doi.org/10.1016/j.envsoft.2016.04.002

Anagnostopoulos GG, Fatichi S, Burlando P 2015. An advanced process-based distributed model for the investigation of rainfall-induced landslides: The effect of process representation and boundary conditions. Water Resour. Res. 51, 7501–7523. https://doi.org/10.1002/2015WR016909

Anderson RS, Anderson SP, Tucker GE 2012. Rock damage and regolith transport by frost: an example of climate modulation of the geomorphology of the critical zone. Earth Surf. Process. Landforms 38, 299–316. https://doi.org/10.1002/esp.3330

Bathurst JC, Moretti G, El-Hames A, Moaven-Hashemi A, Burton A 2005. Scenario modelling of basin-scale, shallow landslide sediment yield, Valsassina, Italian Southern Alps. Nat. Hazards Earth Syst. Sci. 5(2), 189–202. https://doi.org/10.5194/nhess-5-189-2005

Bathurst J, Burton A, Clarke B, Gallart F 2006. Application of the SHETRAN basin-scale, landslide sediment yield model to the Llobregat basin, Spanish Pyrenees. Hydrol. Proc. 20, 3119–3138. https://doi.org/10.1002/hyp.6151

Bathurst JC, Bovolo CI, Cisneros F 2010. Modelling the effect of forest cover on shallow landslides at the river basin scale. Ecol. Eng. 36(3), 317–327. https://doi.org/10.1016/j.ecoleng.2009.05.001

Baum RL, Savage WZ, Godt J 2008. TRIGRS—a Fortran program for transient rainfall infiltration and grid-based regional slope-stability analysis. Open-file report 02-424, 35p. U.S. Geol. Surv. https://doi.org/10.3133/ofr20081159

Befus KM, Sheehan AF, Leopold M, Anderson SP, Anderson RS 2011. Seismic Constraints on Critical Zone Architecture, Boulder Creek Watershed, Front Range, Colorado. Vadose Zone J. 10(4), 1342. https://doi.org/10.2136/vzj2010.0108er

Beland Lindahl K, Baker S, Waldenström C 2013. Place Perceptions and Controversies over Forest Management: Exploring a Swedish Example. J. Environ. Policy Plan. 15, 201–223. https://doi.org/10.1080/1523908X.2012.753316

Bellugi D, Milledge DG, Dietrich WE, Perron JT, McKean J 2015. Predicting shallow landslide size and location across a natural landscape: Application of a spectral clustering search algorithm. J. Geophys. Res. Earth Surf. 120(12), 2552–2585. http://dx.doi.org/10.1002/2015JF003520

Benavides R, Douglas G, Osoro K 2009. Silvopastoralism in New Zealand: review of effects of evergreen and deciduous trees on pasture dynamics. Agroforestry Sys. 76(2), 327–350. https://doi.org/10.1007/s10457-008-9186-6

Benda L 1990. The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA. Earth Surf. Proc. Landforms 15, 457–466.

Benda L, Dunne T 1997a. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. Water Resour. Res. 33, 2849–2863. https://doi.org/10.1029/97WR02388

Benda L, Dunne T 1997b. Stochastic forcing of sediment routing and storage in channel networks. Water Resour. Res. 33, 2865–2880. https://doi.org/10.1029/97WR02387

Bergin DO, Kimberley MO, Marden M 1995. Protective value of regenerating tea tree stands on erosion-prone hill country, East Coast, North Island, New Zealand. NZ J. For. Sci. 25(1), 3–19.

Berti M, Martina MLV, Franceschini S, Pignone S, Simoni A, Pizziolo M 2012. Probabilistic rainfall thresholds for landslide occurrence using a Bayesian approach. J. Geophys. Res. Earth Surf. 117, F04006. https://doi.org/10.1029/2012JF002367

Betts H, Basher L, Dymond J, Herzig A, Marden M, Phillips C 2017. Development of a landslide component for a sediment budget model. Environ. Mod. Softw. 92, 28–39. https://doi.org/10.1016/j.envsoft.2017.02.003

Bischetti GB, Chiaradia E 2010. Calibration of distributed shallow landslide models in forested landscapes. J. Ag. Eng. 3, 23–35. https://doi.org/10.4081/jae.2010.3.23

Blahut J, van Westen CJ, Sterlacchini S 2010. Analysis of landslide inventories for accurate prediction of debris-flow source areas. Geomorphology 119(1–2), 36–51. https://doi.org/10.1016/j.geomorph.2010.02.017

Bovolo CI, Bathurst JC 2011. Modelling catchment-scale shallow landslide occurrence and sediment yield as a function of rainfall return period. Hydrol. Proc. 26(4), 579–596. https://doi.org/10.1002/hyp.8158

Bozzolan E, Holcombe E, Pianosi F, Wagener T 2020. Including informal housing in slope stability analysis – an application to a data-scarce location in the humid tropics. Nat. Hazards Earth Syst. Sci. Discuss. 1–20. https://doi.org/10.5194/nhess-2020-207

Brantley SL, McDowell WH, Dietrich WE, White TS, Kumar P, Anderson SP, Chorover J, Ann Lohse K, Bales RC, Richter DD, Grant G, Gaillardet J 2017. Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth. Earth Surf. Dyn. 5, 841–860. https://doi.org/10.5194/esurf-5-841-2017

Brardinoni F, Slaymaker O, Hassan MA 2003. Landslide inventory in a rugged forested watershed. A comparison between air-photo and field survey data. Geomorphology 54, 179–196. https://doi.org/10.1016/S0169-555X(02)00355-0

Brunetti MT, Melillo M, Peruccacci S, Ciabatta L, Brocca L 2018. How far are we from the use of satellite rainfall products in landslide forecasting? Remote Sens. Env. 210, 65–75. https://doi.org/10.1016/j.rse.2018.03.016

Bunn MD, Leshchinsky B, Olsen MJ, Booth A 2019. A Simplified, Object-Based Framework for Efficient Landslide Inventorying Using LIDAR Digital Elevation Model Derivatives. Remote Sensing 11(3), 29. https://doi.org/10.3390/rs11030303

Burrows K, Walters RJ, Milledge D, Spaans K, Densmore AL 2019. A New Method for Large-Scale Landslide Classification from Satellite Radar. Remote Sensing 11(3), 237. https://doi.org/10.3390/rs11030237

Burton A, Bathurst JC 1998. Physically based modelling of shallow landslide sediment yield at a catchment scale. Environ. Geol. 35, 89–99. https://doi.org/10.1002/hyp.8158

Caine N 1980. The rainfall intensity-duration control of shallow landslides and debris flows: An update. Geogr. Ann. Ser. Phys. Geogr. 62, 23–27. https://doi.org/10.2307/520449

Campbell RH 1975. Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California. US Geol Surv Prof Pap 851, 51 p. https://doi.org/10.3133/pp851

Cardinali M, Reichenbach P, Guzzetti F, Ardizzone F, Antonini G, Galli M, Cacciano M, Castellani M, Salvati P 2002. A geomorphological approach to the estimation of landslide hazards and risks in Umbria, Central Italy. Nat. Hazards Earth Syst. Sci. 2(1/2), 57–72. https://doi.org/10.5194/nhess-2-57-2002

Casadei M, Dietrich WE 2003. Controls on shallow landslide size. In Proceedings of the 3rd International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment (Vol. 1, pp. 91–101). Davos, Switzerland.

Casadei M, Dietrich WE, Miller NL 2003. Testing a model for predicting the timing and location of shallow landslide initiation in soil-mantled landscapes. Earth Surf. Proc. Landforms 28(9), 925–950. https://doi.org/10.1002/esp.470

Cerovski-Darriau C, Roering JJ, Marden M, Palmer AS, Bilderback EL 2014. Quantifying temporal variations in landslide-driven sediment production by reconstructing paleolandscapes using tephrochronology and lidar: Waipaoa River, New Zealand. Geochem. Geophys. Geosystems 15(11), 4117–4136. https://doi.org/10.1002/2014GC005467

Chang K-T, Chiang S-H 2009. An integrated model for predicting rainfall-induced landslides. Geomorphology 105(3), 366–373. https://doi.org/10.1016/j.geomorph.2008.10.012

Chatwin SC, Howes DE, Schwab JW, Swanston DN 1994. A guide for management of landslide-prone terrain in the Pacific Northwest Second Edition. Land Management Handbook. 220 p. https://www.for.gov.bc.ca/hfd/pubs/docs/lmh/Lmh18.pdf

Chen C-W, Chen H, Oguchi T 2016. Distributions of landslides, vegetation, and related sediment yields during typhoon events in northwestern Taiwan. Geomorphology 273, 1–13. https://doi.org/10.1016/j.geomorph.2016.08.012

Chen Y, Chang K, Lee H, Chiang S 2015. Average landslide erosion rate at the watershed scale in southern Taiwan estimated from magnitude and frequency of rainfall. Geomorphology 228, 756–764. https://doi.org/http://dx.doi.org/10.1016/j.geomorph.2014.07.022

Chiang S-H, Chang K-T 2009. Application of radar data to modeling rainfall-induced landslides. Geomorphology 103, 299–309. https://doi.org/10.1016/j.geomorph.2008.06.012

Chiaradia EA, Bischetti GB, Vergani C 2012. Incorporating the effect of root systems of forest species into spatially distributed models of shallow landslides. International Journal of Forest, Soil and Erosion (IJFSE) 2(3).

Cislaghi A, Chiaradia E, Bischetti GB 2017. Including root reinforcement variability in a probabilistic 3-D stability model. Earth Surf. Proc. Landforms 42, 1789–1806. https://doi.org/10.1002/esp.4127

Cislaghi A, Bischetti GB 2019. Source areas, connectivity, and delivery rate of sediments in mountainous-forested hillslopes: A probabilistic approach. Sci. Tot. Environ. 652, 1168–1186. https://doi.org/10.1016/j.scitotenv.2018.10.318

Cohen D, Schwarz M 2017. Tree-root control of shallow landslides. Earth Surf. Dynam. 5(3), 451–477. https://doi.org/10.5194/esurf-5-451-2017

Collison A, Griffiths J 2004. Modelling slope instability. In: Wainwright J, Mulligan M (Eds.), Environmental Modelling: Finding Simplicity in Complexity. Wiley, Chichester, UK, pp. 197–209.

Croissant T, Steer P, Lague D, Davy P, Jeandet L, Hilton RG 2019. Seismic cycles, earthquakes, landslides and sediment fluxes: Linking tectonics to surface processes using a reduced-complexity model. Geomorphology 339 (12). https://doi.org/10.1016/j.geomorph.2019.04.017

Crozier M 2005. Multiple-occurrence regional landslide events in New Zealand: Hazard management issues. Landslides 2(4), 247–256. https://doi.org/10.1007/s10346-005-0019-7

Crozier MJ 2017. A proposed cell model for multiple-occurrence regional landslide events: Implications for landslide susceptibility mapping. Geomorphology 295(Supplement C), 480–488. https://doi.org/10.1016/j.geomorph.2017.07.032

Crozier M, Preston N 1999. Modelling changes in terrain resistance as a component of landform evolution in unstable hill country. In: Hergarten S and Neugebauer HJ (Eds) Process Modelling and Landform Evolution. Lecture Notes in Earth Sciences 78. Springer-Verlag Heidelberg. Pp. 267–284. https://doi.org/10.1007/BFb0009730

Crozier MJ, Vaughan EE, Tippett JM 1990. Relative instability of colluvium-filled bedrock depressions. Earth Surf. Process. Landforms 15, 329–339. https://doi.org/10.1002/esp.3290150404

Danjon F, Barker DH, Drexhage M, Stokes A 2008. Using Three-dimensional Plant Root Architecture in Models of Shallow-slope Stability. Ann Bot 101(8), 1281–1293. https://doi.org/10.1093/aob/mcm199

Dazio EPR, Conedera M, Schwarz M 2018. Impact of different chestnut coppice managements on root reinforcement and shallow landslide susceptibility. For. Ecol. Mgmt. 417, 63–76. https://doi.org/10.1016/j.foreco.2018.02.031

DeRose RC, Trustrum NA, Blaschke PM 1991. Geomorphic change implied by regolith - slope relationships on steepland hillslopes, Taranaki, New Zealand. Catena 18(5), 489–514. https://doi.org/10.1016/0341-8162(91)90051-X

Destro E, Marra F, Nikolopoulos EI, Zoccatelli D, Creutin JD, Borga M 2017. Spatial estimation of debris flows-triggering rainfall and its dependence on rainfall return period. Geomorphology 278, 269–279. https://doi.org/10.1016/j.geomorph.2016.11.019

Dhakal AS, Sidle RC 2003. Long-term modelling of landslides for different forest management practices. Earth Surf. Proc. Landforms 28(8), 853–868. https://doi.org/10.1002/esp.499

Dietrich WE, Dunne T 1978. Sediment budget for a small catchment in mountainous terrain. Z. Geomorph. N. F. 576.

Dietrich WE, McKean J, Bellugi D, Perron T 2007. The prediction of shallow landslide location and size using a multidimensional landslide analysis in a digital terrain model. In Proceedings of the Fourth International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment (DFHM-4), edited by, CL Chen and JJ Major, 12 pp., Millpress, Rotterdam, Netherlands.

Dominati EJ, Mackay A, Lynch B, Heath N, Millner I 2014. An ecosystem services approach to the quantification of shallow mass movement erosion and the value of soil conservation practices. Ecosystem Services 9, 204–215. https://doi.org/10.1016/j.ecoser.2014.06.006

D'Odorico P, Fagherazzi S 2003. A probabilistic model of rainfall-triggered shallow landslides in hollows: A long-term analysis. Water Resources Research 39(9). https://doi.org/10.1029/2002WR001595

Dorren L, Schwarz M 2016. Quantifying the Stabilizing Effect of Forests on Shallow Landslide-Prone Slopes using SlideforNet.  Interpraevent. Lucerne, Switzerland. Pp 78–79.

Douglas GB, McIvor IR, Manderson AK, Koolaard JP, Todd M, Braaksma S, Gray RAJ 2011. Reducing shallow landslide occurrence in pastoral hill country using wide-spaced trees. Land Deg. Development 24 (2), 103–114. https://doi.org/10.1002/ldr.1106

Dymond JR, Ausseil A-G, Shepherd JD, Buettner L 2006. Validation of a region-wide model of landslide susceptibility in the Manawatu–Wanganui region of New Zealand. Geomorphology 74(1–4), 70–79. https://doi.org/10.1016/j.geomorph.2005.08.005

Dymond JR, Betts HD, Schierlitz CS 2010. An erosion model for evaluating regional land-use scenarios. Environ. Mod. Softw. 25(3), 289–298. https://doi.org/10.1016/j.envsoft.2009.09.011

Dymond JR, De Rose R 2011. Modelling landscape evolution in the Waipaoa catchment, New Zealand — A phenomenological approach. Geomorphology 132(1–2), 29–34. https://doi.org/10.1016/j.geomorph.2011.04.032

Dymond JR, Herzig A, Basher L, Betts HD, Marden M, Phillips CJ, Ausseil A-GE, Palmer DJ, Clark M, Roygard J 2016. Development of a New Zealand SedNet model for assessment of catchment-wide soil-conservation works. Geomorphology 257, 85–93. https://doi.org/10.1016/j.geomorph.2015.12.022

Elliott AH, Basher L 2011. Modelling sediment flux: A review of New Zealand catchment-scale approaches. J. Hydrol. (NZ) 50(1), 143–160.

Ewen J 1995. Contaminant transport component of the catchment modelling system (SHETRAN). In: Trudgill ST (ed) Solute modelling in catchment systems. Wiley, Chichester, UK, pp 417–441

European Water Framework Directive 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal L 327, 22/12/2000 P. 0001 – 0073. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32000L0060

Fahey BD, Marden M, Phillips CJ 2003. Sediment yields associated with plantation forestry, coastal Hawkes Bay, north Island, New Zealand. J. Hydrol. (NZ) 42(1), 27-38. https://www.jstor.org/stable/43944858

Fan X, Scaringi G, Korup O, West AJ, van Westen CJ, Tanyas H, Hovius N, Hales TC, Jibson RW, Allstadt KE, Zhang L, Evans SG, Xu C, Li G, Pei X, Xu Q, Huang R 2019. Earthquake-Induced Chains of Geologic Hazards: Patterns, Mechanisms, and Impacts. Rev. Geophys. https://doi.org/10.1029/2018RG000626

Flepp G, Robyr R, Scotti R, Giadrossich F, Conedera M, Vacchiano G, Fischer C, Ammann P, May D, Schwarz M 2021. Temporal dynamics of root reinforcement in European spruce forests. Forests 12(6), 815. https://doi.org/10.3390/f12060815

Forbes K, Broadhead J 2011. Forests and landslides. The role of trees and forests in the prevention of landslides and rehabilitation of landslide-affected areas in Asia. FAO RAP Publication 2011/19. http://www.fao.org/3/i3245e/i3245e.pdf

Frattini P, Crosta G, Sosio R 2009. Approaches for defining thresholds and return periods for rainfall-triggered shallow landslides. Hydrol. Proc. 23(10), 1444–1460. https://doi.org/10.1002/hyp.7269

Fuller IC, Riedler RA, Bell R, Marden M, Glade T 2016. Landslide-driven erosion and slope–channel coupling in steep, forested terrain, Ruahine Ranges, New Zealand, 1946–2011. Catena 142, 252–268. https://doi.org/10.1016/j.catena.2016.03.019

Gabet EJ, Dunne T 2002. Landslides on coastal sage-scrub and grassland hillslopes in a severe El Niño winter: The effects of vegetation conversion on sediment delivery. Geological Society of America Bulletin, 114(8), 983–990. https://doi.org/10.1130/0016-7606(2002)114<0983:LOCSSA>2.0.CO;2

Gabet EJ, Dunne T 2003. A stochastic sediment delivery model for a steep Mediterranean landscape, Water Resour. Res. 39(9), 1–12. https://doi.org/10.1029/2003WR002341

Gabet EJ, Mudd SM 2010. Bedrock erosion by root fracture and tree throw: A coupled biogeomorphic model to explore the humped soil production function and the persistence of hillslope soils. J. Geophys. Res. 115(F4). https://doi.org/10.1029/2009JF001526

Gabet EJ, Mudd SM, Milodowski DT, Yoo K, Hurst MD, Dosseto A 2015. Local topography and erosion rate control regolith thickness along a ridgeline in the Sierra Nevada, California. Earth Surf. Proc. Landforms, 40(13), 1779–1790. https://doi.org/10.1002/esp.3754

García-Ruiz JM, Beguería S, Arnáez J, Sanjuán Y, Lana-Renault N, Gómez-Villar A, Álvarez-Martínez J, Coba-Pérez P 2017. Deforestation induces shallow landsliding in the montane and subalpine belts of the Urbión Mountains, Iberian Range, Northern Spain. Geomorphology 296, 31–44. https://doi.org/10.1016/j.geomorph.2017.08.016

Gariano SL, Piciullo L, Segoni S 2018. Latest progresses in rainfall thresholds, a fundamental component for regional landslide early warning systems. 20th EGU General Assembly, EGU2018, Proceedings from the conference held 4-13 April, 2018 in Vienna, Austria, p.8432. https://meetingorganizer.copernicus.org/EGU2018/EGU2018-8432.pdf

Ghestem M, Sidle RC, Stokes A 2011. The influence of plant root systems on subsurface flow: implications for slope stability. Bioscience 61, 869–879. https://doi.org/10.1525/bio.2011.61.11.6

Giadrossich F, Schwarz M, Marden M, Marrosu R, Phillips C 2020. Minimum representative root distribution sampling for calculating slope stability in *Pinus radiata* D.Don plantations in New Zealand. NZ J. For. Sci. 50. https://doi.org/10.33494/nzjfs502020x68x

Glade T 1998. Establishing the frequency and magnitude of landslide-triggering rainstorm events in New Zealand. Environ. Geol. 35(2), 160–174. https://doi.org/10.1007/s002540050302

Glade T 2003. Landslide occurrence as a response to land use change: a review of evidence from New Zealand. Catena 51(3–4), 297–314. https://doi.org/10.1016/S0341-8162(02)00170-4

Glade T, Crozier M 1996. Towards a national landslide information base for New Zealand. NZ Geographer 52(1), 29–40. https://doi.org/10.1111/j.1745-7939.1996.tb00461.x

Goetz JN, Guthrie RH, Brenning A 2015. Forest harvesting is associated with increased landslide activity during an extreme rainstorm on Vancouver Island, Canada. Nat. Haz. Earth Syst. Sci. 15(6), 1311–1330. https://doi.org/10.5194/nhess-15-1311-2015

González-Ollauri A, Mickovski S 2017. Plant-Best: A novel plant selection tool for slope protection. Ecol. Eng. 106, 154–173. https://doi.org/10.1016/j.ecoleng.2017.04.066

Greenway DR 1987. Vegetation and slope stability. In: Anderson MG, Richards KS (Eds.), Slope Stability, Geotechnical Engineering and Geomorphology. John Wiley & Sons, Chichester, UK, pp. 187–230.

Guthrie RH 2009. The occurrence and behaviour of rainfall-triggered landslides in Coastal British Columbia. Unpublished thesis, University of Waterloo. 176 p. https://www.for.gov.bc.ca/hfd/library/documents/bib109022_low_res.pdf

Guo W-Z, Chen Z-X, Wang W-L, Gao W-W, Guo M-M, Kang H-L, Li P-F, Wang W-X, Zhao M 2019. Telling a different story: The promote role of vegetation in the initiation of shallow landslides during rainfall on the Chinese Loess Plateau. Geomorphology: 106879. https://doi.org/10.1016/j.geomorph.2019.106879

Guzzetti F, Carrara A, Cardinali M, Reichenbach P 1999. Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology 31, 181–216. https://doi.org/10.1016/S0169-555X(99)00078-1

Guzzetti F, Cardinalli M, Reichenbach P, Cipolla , Sebastini C, Galli M, Salvati P 2004. Landslides triggered by the 23 November 2000 rainfall event in the Imperia Provence, Western Liguria, Italy. Eng. Geol. 73, 229–245. https://doi.org/10.1016/j.enggeo.2004.01.006

Guzzetti F, Reichenbach P, Cardinali M, Galli M, Ardizzone F 2005. Probabilistic landslide hazard assessment at the basin scale. Geomorphology 72, 272–299. http://dx.doi.org/10.1016/j.geomorph.2005.06.002

Guzzetti F, Reichenbach P, Ardizzone F, Cardinali M, Galli M 2006. Estimating the quality of landslide susceptibility models. Geomorphology, 81, 166–184. https://doi.org/10.1016/j.geomorph.2006.04.007

Guzzetti F, Peruccacci S, Rossi M, Stark PC 2007. Rainfall thresholds for the initiation of landslides in central and southern Europe. Met. Atmos. Phys. 98(3), 239–26. https://doi.org/10.1007/s00703-007-0262-7

Guzzetti F, Peruccacci S, Rossi M, Stark CP 2008. The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides, 5, 3–17. https://doi.org/10.1007/s10346-007-0112-1

Hack JT, Goodlett JC 1960. Geomorphology and forest ecology of a mountain region in the central Appalachians. USGS Prof. Pap., 347, 66. https://doi.org/10.3133/pp347

Hales TC 2018. Modelling biome-scale root reinforcement and slope stability. Earth Surf. Proc. Landforms 43(10), 2157–2166. https://doi.org/10.1002/esp.4381

Hales TC, Ford CR, Hwang T, Vose JM, Band LE 2009. Topographic and ecologic controls on root reinforcement. J. Geophys. Res., 114. https://doi.org/10.1029/2008JF001168

Heaphy MJ, Lowe DJ, Palmer DJ, Jones HS, Gielen GJHP, Oliver GR, Pearce SH 2014. Assessing drivers of plantation forest productivity on eroded and non-eroded soils in hilly land, eastern North Island, New Zealand. NZ J. For. Sci. 44, 24. https://doi.org/10.1186/s40490-014-0024-5

Heleno S, Matias M, Pina P, Sousa AJ 2016. Semiautomated object-based classification of rain-induced landslides with VHR multispectral images on Madeira Island. Nat. Hazards Earth Syst. Sci. 16, 1035–1048. https://doi.org/10.5194/nhess-16-1035-2016

Hicks DL 1990. Landslide damage to hill country under pasture, pine plantation, scrub, and bush in Taranaki. DSIR Land Resources Technical Record. 19 p.

Hicks DL 1991. Erosion under pasture, pine plantations, scrub and indigenous forest: a comparison from Cyclone Bola. New Zealand Forestry (November), 21–22.

Hicks DM, Gomez B, Trustrum NA 2000. Erosion thresholds and suspended sediment yields, Waipaoa River Basin, New Zealand, Wat. Resour. Res., 36, 1129–1142.

Hölbling D, Betts H, Spiekermann R, Phillips C 2016. Identifying Spatio-Temporal Landslide Hotspots on North Island, New Zealand, by Analyzing Historical and Recent Aerial Photography. Geosciences, 6 (4). https://doi.org/10.3390/geosciences6040048

Huang J, Hales TC, Huang R, Ju N, Li Q, Huang Y 2020. A hybrid machine-learning model to estimate potential debris-flow volumes. Geomorphology 367, 107333. https://doi.org/10.1016/j.geomorph.2020.107333

Hubble TCT, Airey DW, Sealey HK, De Carli EV, Clarke SL 2013. A little cohesion goes a long way: Estimating appropriate values of additional root cohesion for evaluating slope stability in the Eastern Australian highlands. Ecol. Eng. 61, 621–632. https://doi.org/10.1029/1999WR900340

Hungr O, Leroueil S, Picarelli L 2014. The Varnes classification of landslide types, an update. Landslides 11(2),167–194. https://doi.org/10.1007/s10346-013-0436-y

Hurst MD, Mudd SM, Yoo K, Attal M, Walcott R 2013. Influence of lithology on hillslope morphology and response to tectonic forcing in the northern Sierra Nevada of California. J. Geophys. Res. Earth Surf. 118(2): 832–851. https://doi.org/10.1002/jgrf.20049

Hwang T, Band LE, Hales TC, Miniat CF, Vose JM, Bolstad PV, Miles B, Price K 2015. Simulating vegetation controls on hurricane-induced shallow landslides with a distributed ecohydrological model. Journal of Geophysical Research Biogeoscience 120, 361–378. https://doi.org/10.1002/2014JG002824

Imaizumi F, Sidle RC 2012. Effect of forest harvesting on hydrogeomorphic processes in steep terrain of central Japan. Geomorphology 169, 109–122. https://doi.org/10.1016/j.geomorph.2012.04.017

Imaizumi F, Sidle RC, Kamei R 2008. Effects of forest harvesting on occurrence of landslides and debris flows in steep terrain of central Japan. Earth Surf. Process. Landf. 33, 827–840. https://doi.org/10.1002/esp.1574

Istanbulluoglu E, Tarboton DG, Pack RT, Luce CH 2004. Modeling of the interactions between forest vegetation, disturbances, and sediment yields, J. Geophys. Res., 109, F01009. https://doi.org/10.1029/2003JF000041

Iverson RM 2000. Landslide triggering by rain infiltration. Water Res. Res., 36(7), 1897–1910. https://doi.org/10.1029/2000WR900090

Jacobs L, Kervyn M, Reichenbach P, Rossi M, Marchesini I, Alvioli M, Dewitte O 2020. Regional susceptibility assessments with heterogeneous landslide information: Slope unit- vs. pixel-based approach. Geomorphology 356, 107084. https://doi.org/10.1016/j.geomorph.2020.107084

Jones KE, Preston NJ 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. https://doi.org/10.1016/j.geomorph.2011.12.037

Jordan P 2002. Landslide frequency and terrain attributes in Arrow and Kootenay lakes forest districts. In: Jordan P, Orban J (eds) Terrain stability and forest management in the interior of British Columbia: workshop proceedings. May 23–25, 2001, Nelson. B.C. Ministry of Forests, Research Branch, Victoria. Technical Report 003, pp 80–102.

Keim RF, Skaugset AE 2003. Modelling effects of forest canopies on slope stability, 1467 (November 2002), Hydrol. Proc. 17(7),1457–1467. https://doi.org/10.1002/hyp.5121

Kirchner JW, Finkel RC, Riebe CS, Granger DE, Clayton JL, King JG, and Megahan WF 2001. Mountain erosion over 10 yr, 10 k. y., and 10 m. y. time scales. Geology 29, 591–594. https://www.fs.fed.us/rm/pubs_other/rmrs_2001_clayton_j001.pdf

Lehmann P, Or D 2012. Hydromechanical triggering of landslides: From progressive local failures to mass release. Water Resour. Res. 48, 1–24. https://doi.org/10.1029/2011WR010947

Liu Z, Gilbert G, Cepeda JM, Lysdahl AOK, Piciullo L, Hefre H, Lacasse S 2021. Modelling of shallow landslides with machine learning algorithms. Geosci. Front. 12, 385–393. https://doi.org/10.1016/j.gsf.2020.04.014

Lu S-Y, Cheng JD, Brooks KN 2001. Managing forests for watershed protection in Taiwan. For. Ecol. Man. 143(1), 77–85. https://doi.org/10.1016/S0378-1127(00)00507-7

Malamud BD, Turcotte DL, Guzzetti F, Reichenbach P 2004. Landslide inventories and their statistical properties. Earth Surf. Proc. Landforms 29. https://doi.org/10.1002/esp.1064

Marc O, Hovius N, Meunier P, Uchida T, Hayashi S 2015. Transient changes of landslide rates after earthquakes. Geology 43, 883–886. https://doi.org/10.1130/G36961.1

Marden M 2012. Effectiveness of reforestation in erosion mitigation and implications for future sediment yields, East Coast catchments, New Zealand: A review. NZ Geographer 68(1), 24–35. https://doi.org/10.1111/j.1745-7939.2012.01218.x

Marden M, Rowan D 1993. Protective value of vegetation on Tertiary terrain before and during Cyclone Bola, East Coast, North Island, New Zealand. NZ J. For. Sci. 23(3), 255–263. https://www.scionresearch.com/__data/assets/pdf_file/0017/17702/NZJFS2331993MARDON255_263.pdf

Marden M, Herzig A, Basher L 2014. Erosion process contribution to sediment yield before and after the establishment of exotic forest: Waipaoa catchment, New Zealand. Geomorphology 226(0), 162–174. https://doi.org/10.1016/j.geomorph.2014.08.007

Masi EB, Segoni S, Tofani V 2021. Root Reinforcement in Slope Stability Models: A Review. Geosciences 11, 212. https://doi.org/10.3390/geosciences11050212

McCoy SW 2015. Infrequent, large-magnitude debris flows are important agents of landscape change. Geology 43(5), 463–464. https://doi.org/10.1130/focus052015.1

McGuire LA, Rengers FK, Kean JW, Coe JA, Mirus BB, Baum RL, Godt JW 2016. Elucidating the role of vegetation in the initiation of rainfall-induced shallow landslides: Insights from an extreme rainfall event in the Colorado Front Range. Geophys. Res. Letters 43(17), 9084–9092. https://doi.org/10.1002/2016GL070741

McIvor IR, Douglas GB, Hurst SE, Hussain Z, Foote AG 2008. Structural root growth of young Veronese poplars on erodible slopes in the southern North Island, New Zealand. Agroforestry Systems 72(1), 75–86. https://doi.org/10.1007/s10457-007-9090-5

McIvor IR, Douglas G, Dymond J, Eyles GO, Marden M 2011. Pastoral Hill Slope Erosion in New Zealand and the Role of Poplar and Willow Trees in Its Reduction. Soil Erosion Issues in Agriculture. Pp. 257–278. DOI: 10.5772/24365

Milledge DG, Bellugi D, McKean JA, Densmore AL, Dietrich WE 2014. A multidimensional stability model for predicting shallow landslide size and shape across landscapes. J. Geophys. Res. Earth Surf. 119(11), 2481–2504. https://doi.org/10.1002/2014JF003135

Minder JR, Roe GH, Montgomery DR 2009. Spatial patterns of rainfall and shallow landslide susceptibility. Water Resour. Res. 45(4). https://doi.org/10.1029/2008WR007027

Montgomery DR, Dietrich WE 1994. A physically based model for the topographic control of shallow landsliding. Water Resour. Res. 30 (4), 1153–1171. https://doi.org/10.1029/93WR02979

Montgomery DR, Dietrich WE, Torres R, Anderson P, Heffner JT, Loague K 1997. Hydrologic response of a steep , unchanneled valley to natural and applied rainfall. Water Resour. Res. 33(1), 91–109. https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/96WR02985

Montgomery DR, Schmidt KM, Greenberg HM, Dietrich WE 2000. Forest clearing and regional landsliding. Geology 28(4), 311-314. https://doi.org/10.1130/0091-7613(2000)28<311:FCARL>2.0.CO;2

Moreno-de-las-Heras M, Lindenberger F, Latron J, Lana-Renault N, Llorens P, Arnáez J, Romero-Díaz A, Gallart F 2019. Hydro-geomorphological consequences of the abandonment of agricultural terraces in the Mediterranean region: Key controlling factors and landscape stability patterns. Geomorphology 333, 73–91. https://doi.org/10.1016/j.geomorph.2019.02.014

Nikolopoulos EI, Crema S, Marchi L, Marra F, Guzzetti F, Borga M 2014. Impact of uncertainty in rainfall estimation on the identification of rainfall thresholds for debris flow occurrence. Geomorphology 221(0), 286–297. https://doi.org/10.1016/j.geomorph.2014.06.015

Moos C, Bebi P, Graf F, Mattli J, Rickli C, Schwarz M 2016. How does forest structure affect root reinforcement and susceptibility to shallow landslides? Earth Surf. Proc. Landforms 41(7), 951–960. https://doi.org/10.1002/esp.3887

Norris JE, Stokes A, Mickovski SB, Cammeraat E, van Beek LPH, Nicol B, Achim A 2008. Slope stability and erosion control: ecotechnological solutions. Dordrecht, Springer.

Nyman P, Smith HG, Sherwin CB, Langhans C, Lane PNJ, Sheridan GJ 2015. Predicting sediment delivery from debris flows after wildfire. Geomorphology 250, 173–186. https://doi.org/10.1016/j.geomorph.2015.08.023

O'Loughlin CL 1974. A Study of Tree Root Strength Deterioration Following Clearfelling. Canadian Journal of Forest Research 4(1): 107–113. https://doi.org/10.1139/x74-016

O'Loughlin C 2005. The protective role of trees in soil conservation. NZ J. For. 49(4), 9–15.

O'Loughlin CL, Pearce AJ 1976. Influence of Cenozoic geology on mass movement and sediment yield response to forest removal, North Westland, New Zealand. Bull. Int. Assoc. Eng. Geol. 14, 41–46.

O'Loughlin C, Watson A 1979. Root-wood strength deterioration in radiata pine after clearfelling. NZ J. For. Sci. 9(3), 284–293. https://www.scionresearch.com/__data/assets/pdf_file/0009/36918/NZJFS931979OLOUGHLIN284_293.pdf

Pack RT, Tarboton DG, Goodwin CN 2001. Assessing Terrain Stability in a GIS using SINMAP, in 15th annual GIS conference, GIS 2001, Vancouver, British Columbia, February 19–22. https://hydrology.usu.edu/sinmap/gis2001.pdf

Page MJ, Trustrum NA, Dymond JR 1994. Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand. Geomorphology 9(3), 169–188. https://doi.org/10.1016/0169-555X(94)90061-2

Page MJ, Reid LM, Lynn IH 1999. Sediment production from Cyclone Bola landslides, Waipaoa catchment. J. Hydrol. (NZ) 38(2), 289–308. https://www.jstor.org/stable/43944823

Palladino MR, Viero A, Turconi L, Brunetti MT, Peruccacci S, Melillo M, Luino F, Deganutti AM, Guzzetti F 2018. Rainfall thresholds for the activation of shallow landslides in the Italian Alps: the role of environmental conditioning factors. Geomorphology 303, 53–67. https://doi.org/10.1016/j.geomorph.2017.11.009

Pan M, Li H, Wood E 2010. Assessing the skill of satellite-based precipitation estimates in hydrologic applications. Water Resour. Res. 46. WO9535. https://doi.org/10.1029/2009WR008290

Parker RL, Hales TC, Mudd SM, Grieve SWD, Constantine JA 2016. Colluvium supply in humid regions limits the frequency of storm-triggered landslides. Scientific Reports 6:34438. https://doi.org/10.1038/srep34438

Pazzi V, Tanteri L, Bicocchi G, D'Ambrosio M, Caselli A, Fanti R 2017. H/V measurements as an effective tool for the reliable detection of landslide slip surfaces: Case studies of Castagnola (La Spezia, Italy) and Roccalbegna (Grosseto, Italy). Physics and Chemistry of the Earth, Parts A/B/C, 98, 136–153. https://doi.org/10.1016/j.pce.2016.10.014

Peeters I, Van Oost K, Govers G, Verstraeten G, Rommens T, Poesen J 2008. The compatibility of erosion data at different temporal scales. Earth and Planetary Science Letters 265(1–2), 138–152. https://doi.org/10.1016/j.epsl.2007.09.040

Peruccacci S, Brunetti MT, Gariano SL, Melillo M, Rossi M, Guzzetti F 2017. Rainfall thresholds for possible landslide occurrence in Italy. Geomorphology 290, 39–57. https://doi.org/10.1016/j.geomorph.2017.03.031

Petschko H, Bell R, Leopold P, Heiss G, Glade T 2013. Landslide inventories for reliable susceptibility maps in Lower Austria. In: C. Margottini PC, K. Sassa (Eds.) ed. Landslide Science and Practice, Vol. 1: Landslide Inventory and Susceptibility and Hazard Zoning. Heidelberg Springer. Pp. 337–343. https://doi.org/10.1007/978-3-642-31325-7_37

Phillips CJ, Marden M 2005. Reforestation schemes to manage regional landslide risk. Landslide Hazard and Risk, John Wiley & Sons Ltd.

Phillips CJ, Watson AJ 1994. Structural tree root research in New Zealand: a review. Lincoln, Canterbury, Manaaki Whenua Press. 1–71 p.

Phillips CJ, Marden M, Pearce AJ 1991. Effectiveness of reforestation in prevention and control of landsliding during large cyclonic storms. In Proceedings of the 19th International Union of Forestry Research Organisation (IUFRO), (pp. 358–361). Montreal, Canada.

Phillips C, Marden M, Basher L 2012. Plantation Forest Harvesting and Landscape Response - What We Know and What We Need to Know. NZ J. For. 56(4), 4–12. http://nzjf.org.nz/free_issues/NZJF56_4_2012/59A6BB16-48B8-46ae-838D-9B787B4B6841.pdf

Phillips CJ, Rey F, Marden M, Liebault F 2013. Revegetation of steeplands in France and New Zealand: geomorphic and policy responses. NZ J. For. Sci. 43(14). https://doi.org/10.1186/1179-5395-43-14

Phillips C, Marden M, Basher LR 2017. Geomorphology and forest management in New Zealand's erodible steeplands: An overview. Geomorphology 307, 109–121. https://doi.org/10.1016/j.geomorph.2017.07.031

Preston NJ 2008. Off-slope sediment delivery from landsliding during a storm, Muriwai Hills, North Island. 325: 237-241. New Zealand sediment dynamics in changing environments. Pp. 237–241. https://iahs.info/uploads/dms/14518.35-237-241-29-325-Preston_sm.pdf

Preti F 2012. Forest protection and protection forest: Tree root degradation over hydrological shallow landslides triggering. Ecological Engineering 61P, 633–645.

Reichenbach P, Rossi M, Malamud BD, Mihir M, Guzzetti F 2018. A review of statistically-based landslide susceptibility models. Earth-Science Reviews 180, 60–91.

Reid LM, Page MJ 2002. Magnitude and frequency of landsliding in a large New Zealand catchment. Geomorphology 49, 71–88.

Renaud FG, Sudmeier-Rieux K, Estrella M, Nehren U 2016. Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice, Advances in Natural and Technological Hazards Research. https://doi.org/10.1007/978-3-319-43633-3_21

Reneau SL, Dietrich WE, Donahue DJ, Jull AJT, Rubin M 1990. Late Quaternary history of colluvial deposition and erosion in hollows, central California Coast Ranges. Geol. Soc. Am. Bull. 102(7), 969–982.

Rengers FK, McGuire LA, Kean JW, Staley DM, Hobley DEJJ 2016. Model simulations of flood and debris flow timing in steep catchments after wildfire. Water Resour. Res. 52, 6041–6061. https://doi.org/10.1002/2015WR018176

Rickli C, Graf F 2009. Effects of forests on shallow landslides - case studies in Switzerland. For. Snow Landsc. Res. 82(1), 33–44.

Roering JJ, Schmidt KM, Stock JD, Dietrich WE, Montgomery DR 2003. Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Coast Range. Can. Geotech. J. 40(2), 237–253. https://doi.org/10.1139/t02-113

Roering JJ, Marshall J, Booth AM, Mort M, Jin QS 2010. Evidence for biotic controls on topography and soil production, Earth Planet. Sci. Lett. 298(1–2), 183–190. https://doi.org/10.1016/j.epsl.2010.07.040

Roering JJ, Gerber M 2005. Fire and the evolution of steep, soil-mantled landscapes. Geology 33, 349–352. https://doi.org/10.1130/G21260.1

Rosser BJ, Ross CW 2011. Recovery of pasture production and soil properties on soil slip scars in erodible siltstone hill country, Wairarapa, New Zealand. NZ J. Ag. Res. 54(1), 23–44. https://doi.org/10.1080/00288233.2010.535489

Rosser B, Dellow S, Haubrock S, Glassey P 2017. New Zealand's National Landslide Database. Landslides 14, 1949–1959. https://doi.org/10.1007/s10346-017-0843-6

Rosser BJ, Dellow S, Ashraf M 2019. Assessment of the use of differencing satellite imagery as a tool for quantifying landslide impacts from significant storms - a case study in the Uawa Catchment, Tolaga Bay.

GNS Science Consultancy Report. 51 p. https://envirolink.govt.nz/assets/Envirolink/1216-NLCC63-Processing-and-classifying-satellite-imagery-to-assess-the-December-2011-landslide-storm-damage-in-the-Nelson-area.pdf

Rossi G, Catani F, Leoni L, Segoni S, Tofani V 2013. HIRESSS: a physically based slope stability simulator for HPC applications, Nat. Hazards Earth Syst. Sci. 13, 151–166, https://doi.org/10.5194/nhess-13-151-2013

Saint Cast C, Meredieu C, Défossez P, Pagès L, Danjon FJP2019. Modelling root system development for anchorage of forest trees up to the mature stage, including acclimation to soil constraints: the case of Pinus pinaster. Plant Soil 439(1), 405–430. https://doi.org/10.1007/s11104-019-04039-4

Salciarini D, Tamagnini C, Conversini P, Rapinesi S 2012. Spatially distributed rainfall thresholds for the initiation of shallow landslides. Natural Hazards 61(1), 229–245. https://doi.org/10.1007/s11069-011-9739-2

Salvatici T, Tofani V, Rossi G, D'Ambrosio M, Tacconi Stefanelli C, Masi EB, Rosi A, Pazzi V, Vannocci P, Petrolo M, Catani F, Ratto S, Stevenin H, Casagli N 2018. Application of a physically based model to forecast shallow landslides at a regional scale, Nat. Hazards Earth Syst. Sci. 18, 1919–1935, https://doi.org/10.5194/nhess-18-1919-2018

Samia J, Temme A, Bregt A, Wallinga J, Guzzetti F, Ardizzone F, Rossi M 2017. Do landslides follow landslides? Insights in path dependency from a multi-temporal landslide inventory. Landslides 14, 547–558. https://doi.org/10.1007/s10346-016-0739-x

Schmaltz EM, Steger S, Glade T 2017. The influence of forest cover on landslide occurrence explored with spatio-temporal information. Geomorphology 290, 250–264. https://doi.org/10.1016/j.geomorph.2017.04.024

Schmaltz E, Mergili M 2018. Integration of root systems into a GIS-based slip surface model: computational experiments in a generic hillslope environment. Landslides. https://doi.org/10.1007/s10346-018-0970-8

Schmidt KM, Roering JJ, Stock JD, Dietrich WE, Montgomery DR, Schaub T 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Can. Geotech. J 38(5), 995–1024. https://doi.org/10.1139/cgj-38-5-995

Schwab JW, Geertsema M 2010. Terrain stability mapping on British Columbia forest lands: an historical perspective. Natural Hazards 53(1), 63–75. https://doi.org/10.1007/s11069-009-9410-3

Schwarz M, Lehmann P, Or D 2010. Quantifying lateral root reinforcement in steep slopes – from a bundle of roots to tree stands. Earth Surf. Proc. Landforms 35(3), 354–367. https://doi.org/10.1002/esp.1927

Schwarz M, Giadrossich F, Cohen D 2013. Modeling root reinforcement using root-failure Weibull survival function. Hydrol. Earth Syst. Sci. Discuss. 10(3), 3843-3868. https://doi.org/10.5194/hess-17-4367-2013

Schwarz M, Dorren L, Thormann JJ 2014. SLIDEFORNET: a web tool for assessing the effect of root reinforcement on shallow landslides. In International Conference, "Analysis and Management of Changing Risks for Natural Hazards", 18–19 November 2014, Padua, Italy.

Schwarz M, Phillips C, Marden M, McIvor IR, Douglas GB, Watson A 2016. Modelling of root reinforcement and erosion control by 'Veronese' poplar on pastoral hill country in New Zealand. NZ J. For. Sci. 46(1), 4. https://doi.org/10.1186/s40490-016-0060-4

Segoni S, Piciullo L, Gariano SL 2018. A review of the recent literature on rainfall thresholds for landslide occurrence. Landslides 15(8), 1483–1501. https://doi.org/10.1007/s10346-018-0966-4

Segoni S, Pappafico G, Luti T, Catani F 2020. Landslide susceptibility assessment in complex geological settings: sensitivity to geological information and insights on its parameterization. Landslides 17, 2443–2353. https://doi.org/10.1007/s10346-019-01340-2

Sidle RC 1992. A theoretical model of the effects of timber harvesting on slope stability. Water Resour. Res. 28(7), 1897–1910. https://doi.org/10.1029/92WR00804

Sidle RC, Pearce AJ, O'Loughlin CL (Eds.) 1985. Hillslope Stability and Land Use, Water Resour. Monogr., vol. 11, edited by RC Sidle et al., 140 pp., AGU, Washington, D. C. https://agupubs.onlinelibrary.wiley.com/doi/book/10.1029/WM011

Sidle RC, Ochiai H 2006. Landslides: Processes, Prediction, and Land Use, American Geophysical Union. 312 p. https://www.wiley.com/en-us/Landslides%3A+Processes%2C+Prediction%2C+and+Land+Use-p-9780875903224

Sidle RC, Bogaard TA 2016. Dynamic earth system and ecological controls of rainfall-initiated landslides. Earth-Science Reviews 159, 275–291. https://doi.org/10.1016/j.earscirev.2016.05.013

Sidle RC, Gomi T, Loaiza Usuga JC, Jarihani B 2017. Hydrogeomorphic processes and scaling issues in the continuum from soil pedons to catchments. Earth-Science Reviews 175, 75–96. https://doi.org/10.1016/j.earscirev.2017.10.010

Sivandran G, Bras RL 2013. Dynamic root distributions in ecohydrological modeling : A case study at Walnut Gulch Experimental Watershed 49, 3292–3305. https://doi.org/10.1002/wrcr.20245

Smith HG, Spiekermann R, Betts H, Neverman AJ 2021. Comparing methods of landslide data acquisition and susceptibility modelling: Examples from New Zealand. Geomorphology: 107660. https://doi.org/10.1016/j.geomorph.2021.107660

Spiekermann R, McColl S, Fuller I, Dymond J, Burkitt L, Smith HG 2021. Quantifying the influence of individual trees on slope stability at landscape scale. J. Env. Man. 286, 112194. https://doi.org/10.1016/j.jenvman.2021.112194

Spiker EC, Gori PL 2003. National Landslide Hazards Mitigation Strategy A Framework for Loss Reduction: U.S. Department of the Interior, U.S. Geological Survey, Circula 1244. https://pubs.usgs.gov/circ/c1244/c1244.pdf

Starkel L 1979. The role of extreme meteorological events in the shaping of mountain relief, Geographica Polonica 41, 13–20.

Stock J, Dietrich WE 2003. Valley incision by debris flows: Evidence of a topographic signature. Water Resour. Res. 39(4). https://doi.org/10.1029/2001WR001057

Stokes A, Douglas G, Fourcaud T, Giadrossich F, Gillies C, Hubble T, Kim J, Loades K, Mao Z, McIvor I and others 2014. Ecological mitigation of hillslope instability: ten key issues facing researchers and practitioners. Plant and Soil 377(1-2), 1–23. https://doi.org/10.1007/s11104-014-2044-6

Swanston D 1985. Proceedings of a workshop on slope stability: problems and solutions in forest management. Portland, Oregon, Pacific Northwest Forest and Range Experiment Station, United States Department of Agriculture. 1–122 p. https://www.fs.fed.us/pnw/pubs/pnw_gtr180.pdf

Tang H, McGuire LA, Rengers FK, Kean JW, Staley DM, Smith JB 2019. Evolution of debris-flow initiation mechanisms and sediment sources during a sequence of post-wildfire rainstorms. J. Geophys. Res. Earth Surf. 1–24. https://doi.org/10.1029/2018jf004837

Temgoua AGT, Kokutse NK, Kavazovic Z 2016. Influence of forest stands and root morphologies on hillslope stability. Ecol. Eng. 95, 622–634. https://doi.org/10.1016/j.ecoleng.2016.06.073

Temgoua AGT, K. Kokutse N, Kavazovic Z, Richard M 2017. A 3D model applied to analyze the mechanical stability of real-world forested hillslopes prone to landslides. Ecol. Eng. 106, 609–619. https://doi.org/10.1016/j.ecoleng.2017.06.043

Thiebes B, Bell R, Glade T, Jäger S, Mayer J, Anderson M, Holcombe L 2014. Integration of a limit-equilibrium model into a landslide early warning system. Landslides 11, 859–875. https://doi.org/10.1007/s10346-013-0416-2

Thomas MA, Rengers FK, Kean JW, Mcguire LA, Staley DM, Barnhart KR, Ebel BA 2021. Postwildfire soil-hydraulic recovery and the persistence of debris flow hazards. J. Geophys. Res. Earth Surf. 126(6). https://doi.org/10.1029/2021JF006091

Tobin B, Cermak J, Chiatante D, Danjon F, Di Iorio A, Dupuy L, Eshel A, Jourdan C, Kalliokoski T, Laiho R and others 2007. Towards developmental modelling of tree root systems. Plant Biosystems 141(3), 481–501. https://doi.org/10.1080/11263500701626283

Tordesillas A, Zhou Z, Batterham R 2018. A data-driven complex systems approach to early prediction of landslides. Mechanics Res. Comm. 92, 137–141. https://doi.org/10.1016/j.mechrescom.2018.08.008

Trustrum NA, Gomez B, Page MJ, Reid LM, Hicks DM 1999. Sediment production, storage and output: the relative role of large magnitude events in steepland catchments. Zeitschrift für Geomorphologie N.F. 115, 71–86. http://hydrologynz.co.nz/downloads/JoHNZ_1999_v38_2_Page.pdf

UNDRR 2020. Ecosystem-Based Disaster Risk Reduction: Implementing Nature-based Solutions for Resilience. United Nations Office for Disaster Risk Reduction – Regional Office for Asia and the Pacific, Bangkok, Thailand 64 p. https://www.undrr.org/publication/ecosystem-based-disaster-risk-reduction-implementing-nature-based-solutions-0

Vanacker V, von Blanckenburg F, Govers G, Molina A, Poesen J, Deckers J, Kubik P 2007. Restoring dense vegetation can slow mountain erosion to near natural benchmark levels. Geology 35, 303–306. https://doi.org/10.1130/G23109A.1

van Asch TW, Malet JP, Beek LP, Amitrano D 2007. Techniques, issues and advances in numerical modelling of landslide hazard. Bull. Soc. Géol. Fr. 178 (2), 65–88. http://dx.doi.org/10.2113/gssgfbull.178.2.65.

van den Eeckhaut M, Hervás J, Jaedicke C, Malet JP, Montanarella L, Nadim F 2011. Statistical modelling of Europe-wide landslide susceptibility using limited landslide inventory data. Landslides 9. https://doi.org/10.1007/s10346-011-0299-z

van den Eeckhaut M, Hervás J 2012. State of the art of national landslide databases in Europe and their potential for assessing landslide susceptibility, hazard and risk. Geomorphology 139–140(0), 545–558. https://doi.org/10.1016/j.geomorph.2011.12.006

Vandromme R, Thiery Y, Bernardie S, Sedan O 2020. ALICE (Assessment of Landslides Induced by Climatic Events): A single tool to integrate shallow and deep landslides for susceptibility and hazard assessment. Geomorphology 367, 107307. https://doi.org/10.1016/j.geomorph.2020.107307

van Westen CJ, Rengers N, Terlien MT, Soeters R 1997. Prediction of the occurrence of slope instability phenomenal through GIS-based hazard zonation. Geol. Rundsch. 86, 404–414. https://doi.org/10.1007/s005310050149

van Westen CJ, Castellanos E, Kuriakose SL 2008. Spatial data for landslide susceptibility, hazard, and vulnerability assessment: an overview. Eng. Geol. 102 (3–4), 112–131. http://dx.doi.org/10.1016/j.enggeo.2008.03.010.

van Zadelhoff FB, Albaba A, Cohen D, Phillips C, Schaefli B, Dorren LKA, Schwarz M 2021. Introducing SlideforMap; a probabilistic finite slope approach for modelling shallow landslide probability in forested situations. Nat. Hazards Earth Syst. Sci. Discuss. 1–33. https://doi.org/10.5194/nhess-2021-140

Vargas-Cuervo G, Rotigliano E, Conoscenti C 2019. Prediction of debris-avalanches and -flows triggered by a tropical storm by using a stochastic approach: An application to the events occurred in Mocoa (Colombia) on 1 April 2017. Geomorphology 339, 31–43. https://doi.org/10.1016/j.geomorph.2019.04.023

Vergani C, Schwarz M, Soldati M, Corda A, Giadrossich F, Chiaradia EA, Morando P, Bassanelli C 2016. Root reinforcement dynamics in subalpine spruce forests following timber harvest: a case study in Canton Schwyz, Switzerland. Catena 143, 275–288. https://doi.org/10.1016/j.catena.2016.03.038

Vergani C, Giadrossich F, Buckley P, Conedera M, Pividori M, Salbitano F, Rauch HS, Lovreglio R, Schwarz M 2017. Root reinforcement dynamics of European coppice woodlands and their effect on shallow landslides: A review. Earth-Science Reviews 167, 88–102. https://doi.org/10.1016/j.earscirev.2017.02.002

von Ruette J, Papritz A, Lehmann P, Rickli C, Or D 2011. Spatial statistical modeling of shallow landslides - Validating predictions for different landslide inventories and rainfall events. Geomorphology 133(1–2), 11–22. https://doi.org/10.1016/j.geomorph.2011.06.010

von Ruette J, Lehmann P, Or D 2013. Rainfall-triggered shallow landslides at catchment scale: Threshold mechanics-based modeling for abruptness and localization. Water Resour. Res. 49(10), 6266–6285. https://doi.org/10.1002/wrcr.20418

Wieczorek GW, Guzzetti F 2000. A review of rainfall thresholds for triggering landslides. Claps P. & Siccardi F. (eds.), Mediterranean Storms, Proceedings Plinius Conference ’99, Maratea, 14-16 October 1999, GNDCI pub. n. 2012. Editoriale Bios, Cosenza, 407-414. http://geomorphology.irpi.cnr.it/publications/repository/public/proceedings/2000/a-review-of-rainfall-thresholds-for-triggering-landslides.pdf/view

Wilkinson AG 1999. Poplars and willows for soil erosion control in New Zealand. Biomass & Bioenergy 16(4), 263–274. https://doi.org/10.1016/S0961-9534(99)00007-0

Wilkinson SN 2008. Testing the capability of a sediment budget model for targeting remediation measures to reduce suspended-sediment yield. Sediment Dynamics in Changing Environments. Proceedings of an international conference in Christchurch, New Zealand, December 2008. IAHS Red Book Publ. 325, 559–566. https://iahs.info/uploads/dms/14560.79-559-566-71-325-Wilkinson.pdf

Wilkinson SN, Prosser IP, Olley JM, Read A 2005. Using sediment budgets to prioritise erosion control in large river systems. River/Catchment Dynamics. Natural Processes and Human Impacts. Proceedings of an international conference in Solsona, Spain, May 2004. IAHS Red Book Publ. 299: 56–64.

Wilson RC, Wieczorek GF 1995. Rainfall thresholds for the initiation of debris flow at La Honda, California. Environmental and Engineering Geoscience, 1 (1) (1995), pp. 11–27. https://doi.org/10.2113/gseegeosci.I.1.11

Wooten RM, Witt AC, Miniat CF, Hales TC, Aldred JL 2016. Frequency and Magnitude of Selected Historical Landslide Events in the Southern Appalachian Highlands of North Carolina and Virginia: Relationships to Rainfall, Geological and Ecohydrological Controls, and Effects, in: Greenberg HC, Collins SB (Eds.), Natural Disturbances and Historic Range of Variation: Type, Frequency, Severity, and Post-Disturbance Structure in Central Hardwood Forests USA. Springer International Publishing, Cham, pp. 203–262. https://doi.org/10.1007/978-3-319-21527-3_9

Wu WM, Sidle RC 1995. A distributed slope stability model for steep forested basins. Water Resour. Res. 31(8), 2097–2110. https://doi.org/10.1029/95WR01136

Wu T 1995. Slope stabilization 7, in Slope Stabilization and Erosion Control: A Bioengineering Approach, vol. 233, edited by RPC Morgan and RJ Rickson, pp. 221–264, E&FN Spon/Chapman and Hall, London.

Wu TH, McKinnell WPIII, Swanston DN 1979. Strength of tree roots and landslides on Prince of Wales Island, Alaska, Can. Geotech. J. 16, 19–33. https://doi.org/10.1139/t79-003

Zieher T, Perzl F, Rössel M, Rutzinger M, Meißl G, Markart G, Geitner C 2016. A multi-annual landslide inventory for the assessment of shallow landslide susceptibility – Two test cases in Vorarlberg, Austria. Geomorphology 259, 40–54. https://doi.org/10.1016/j.geomorph.2016.02.008

Zieher T, Schneider-Muntau B, Mergili MJL 2017. Are real-world shallow landslides reproducible by physically-based models? Four test cases in the Laternser valley, Vorarlberg (Austria). Landslides. https://d-nb.info/1139605585/34