Shallow landslides and vegetation at the catchment scale: a perspective

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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, γ is the unit weight of colluvium, z is colluvium depth, β 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).

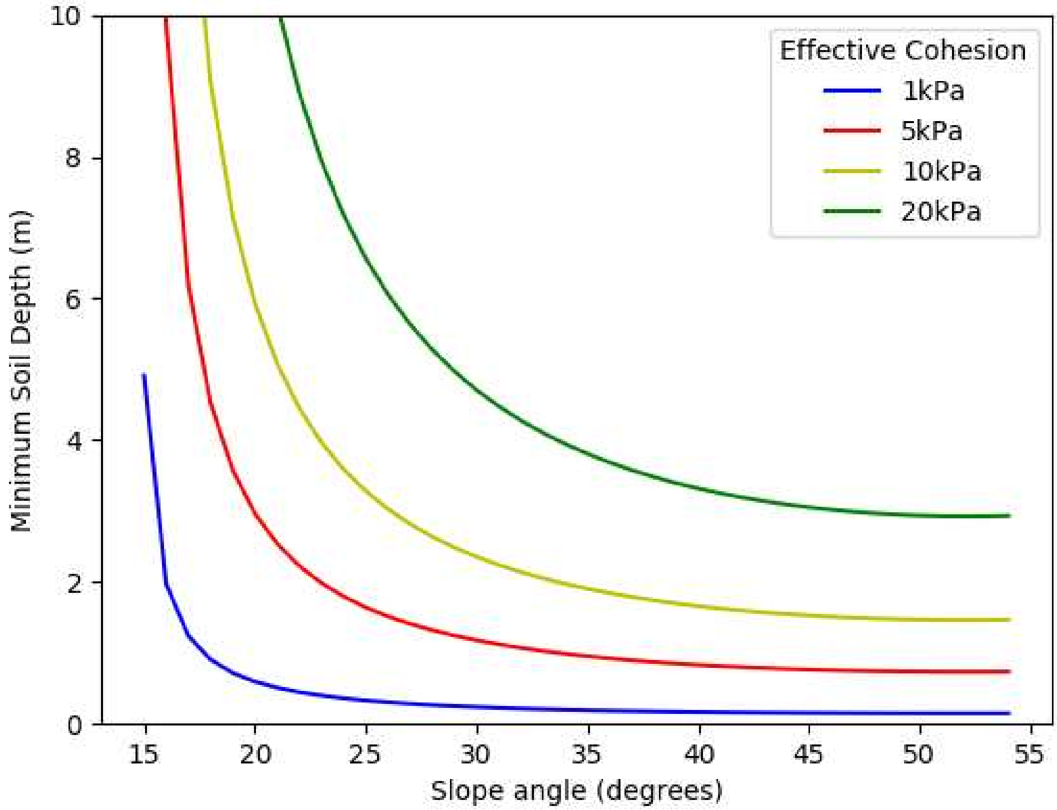

Figure 2 Analytical solutions of the maximum stable regolith depth for hydrostatic pore pressures under different effective cohesion values. These solutions show the striking role that cohesion, which in hillslope regolith is often dominated by root reinforcement, has on stabilising slopes. Similarly, 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 5th 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.

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Competing interests

The authors declare there are no competing interests.

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