

New Zealand Journal of Forestry Science

Increased forest cover and limits on clear-felling could substantially reduce landslide occurrence in Tasman, New Zealand

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(Received for publication 26 January 2020; accepted in revised form 12 November 2020)

Abstract

Background: Landslides can cause substantial environmental, social and economic impacts. Under future climate scenarios the frequency of landslide-triggering events is likely to increase. Land managers, therefore, urgently require reliable high-resolution landslide susceptibility models to inform effective landslide risk assessment and management.

Methods: In this study, gridded rainfall, topography, lithology and land cover surfaces were used to develop a high-resolution (10 m x 10 m) spatial model of landslides that occurred in Tasman, New Zealand during a period when ex-tropical Cyclone Gita brought heavy rain to the region. We separately modelled landslides in the same dataset as a function of the erosion susceptibility classification (ESC) data layer used to determine the level of control applied to forestry activities under the National Environmental Standards for Plantation Forestry (NES-PF). Models were fit using boosted regression trees.

Results: Our preferred model had excellent predictive power (AUROC = 0.93) and included the parameters: aspect, elevation, mid-slope position, land cover, rainfall, slope, and a descriptive seven-class topographical index. Land cover, elevation, rainfall, slope and aspect were the strongest predictors of landslides with the land cover classes seral native vegetation and clear-felled plantation forest predicting higher probabilities of landslides and tall native forest and closed canopy plantation forest predicting lower probabilities of landslides. The ESC was a poor predictor of landslides in the study area (AUROC = 0.65).

Conclusions: Our study shows that accurate, high-resolution landslide probability surfaces can be developed from landslide distribution, land cover, topographical and rainfall data. We also show that landslide occurrence in the Tasman region could be substantially reduced by increasing the extent of permanent forest cover and by limiting clear-fell harvest of plantation forests on landslide-prone slopes. The ESC framework that underpins the NES-PF was a poor predictor of landslides and, therefore, an unreliable basis for regulating forestry activities in the Tasman, New Zealand.

Keywords: Climate change, erosion susceptibility classification, forestry, National Environmental Standards for Plantation Forestry, *Pinus radiata*, slope failure

Introduction

Landslides can cause substantial environmental, social and economic impacts (Dymond et al. 2010; Fahey & Coker 1992; Gordon 2007; Kemp et al. 2011; Krausse et al. 2001; Ryan et al. 2008; Thrush et al. 2004). Land management agencies, therefore, have a strong interest in identifying areas that are susceptible to landslides

and managing human activities that either increase or decrease landslide risk. Substantial effort has also been directed toward understanding the implications of future climate scenarios on the probable frequency of landslide triggering events (Collison et al. 2000; Crozier 2010; Jakob & Lambert 2009; Wood et al. 2020).

In New Zealand and internationally, rainfall intensity and duration, seismic activity, lithology, topography, land cover and land use have all been identified as predictors of landslides (Barrell & Smith Lyttle 2015; Carson & Kirkby 1972; Crozier 2017; Dymond et al. 2010; Dymond et al. 1999; Montgomery & Dietrich 1994). However, the relative importance of these predictors varies at a range of spatial scales, and multiple-occurrence landslide events associated with major storms may not be adequately described by general erosion susceptibility models (Basher et al. 2015a, 2015b; Marden et al. 2015). Change in rainfall intensity and duration and the frequency of severe storms associated with climate change will make rainfall-initiated landslide events more likely in the future (Crozier 2010; Crozier 2017; IPCC 2018), and highlight the need for reliable erosion susceptibility models to inform land management. Using high resolution lithology, topography, land cover, land use and climate surfaces paired with site specific data on previous landslide events, it is possible to accurately model landslide susceptibility and risk at the scale of land use activities (Basher et al. 2015a). Such modelling can help land management agencies identify areas that are susceptible to landslides and to recognise and manage land use activities that increase or decrease landslide risk.

Landslide susceptibility has been predicted using precipitation thresholds (e.g. Caine 1980; Guzzetti et al. 2008; Page et al. 1994) and antecedent moisture in soils (e.g. Crozier 1999). Steeper slopes are generally more prone to failure (Carson & Kirkby 1972), but predictions of failures at near-threshold slopes are difficult without direct measurements of soil properties (e.g. shear strength, cohesion, pore pressure, stabilizing effects of vegetation) as these vary considerably across landscapes (e.g. Claessens et al. 2007).

Studies into landslide susceptibility at local and regional scales in New Zealand have taken a variety of approaches. Most consider underlying lithology and/or soils and topography (slope angle, aspect, relief) as potential predictors of landslide susceptibility (e.g. Barrell & Smith Lyttle 2015; Gao & Maro 2010) and some consider land cover (e.g. Dymond et al. 2010; Glade 2003; Marden & Rowan 1993). A few studies also include landslide triggers such as high-intensity rainfall and earthquakes (e.g. Dellow 2010; Kritikos & Davies 2015), or are tied to particular triggering events (e.g. Massey et al. 2018). Very few consider all these factors together (e.g. Kritikos & Davies 2015), in part due to a paucity of accurate up-to-date land cover data layers with adequate discrimination between land cover classes, but also because triggering events, particularly their frequency and magnitude, are usually considered as part of a risk analysis independently from landslide (erosion) susceptibility (Basher et al. 2015a). However, landslide susceptibility analyses could be improved by including information on the spatial distribution of high-intensity rainfall, where the pattern of precipitation is predictable at local scales (Kritikos & Davies 2015). Landslides in New Zealand are commonly triggered by rainfall (Dellow 2010; Kritikos & Davies 2015) which can

vary substantially over small areas due to interactions between topography and storms (Klik et al. 2015).

Much of the New Zealand landscape that is susceptible to landslides due to high precipitation and steep hillslopes is used for hill country farming and forestry (Basher 2013). Recent rainfall-triggered landslide events in the East Coast, Tasman, and Wanganui-Manawatu regions (Hancox & Wright 2005; Marden & Rowan 1993, 1995; Page et al. 2012, 1994) emphasise the need for better management of these areas. Studies that examine the role of vegetation and land use in detail have shown that forest maturity is an important determinant of landslide susceptibility (Dymond et al. 2010; Marden & Rowan 1993; Reid & Page 2003). Landslide occurrence and sediment yields are lowest in places where forest is well established and forms a continuous canopy, and highest in places where forest is absent or immature, and hasn't developed deep, strong root systems or a continuous canopy (Dymond et al. 2010; Marden et al. 2020; Marden & Rowan 1993). Thus, understanding the role of vegetation and land use in hillslope failure during large storm events is particularly important and may yield actionable strategies for minimising landslide occurrence (Basher 2013; Dymond et al. 2006; Dymond et al. 2010; Marden et al. 2020).

Plantation forestry activities in New Zealand are regulated by the National Environmental Standards for Plantation Forestry (NES-PF) (Ministry for Primary Industries 2017), which are underpinned by an erosion susceptibility classification (ESC) framework developed by Bloomberg et al. (2011) and later revised by Basher et al. (2015b). The ESC ranks all land into four erosion susceptibility classes: low, medium, high and very high. These classes determine the resource consent status of forestry activities. For example, planting and harvesting plantation forest on land with a low, moderate or high ESC ranking are permitted activities, but on land with a very high ESC ranking these activities are controlled and no more than 2 ha can be planted within a calendar year or harvested within any 3-month period. Thus, the ESC has a strong influence on the level of regulation applied to forestry activities. However, the coarse spatial resolution of the ESC may be ill-suited to managing forestry activities at the scale of forestry operations (Basher et al. 2015b).

In this study, we modelled landslides that occurred in the Tasman region of New Zealand between summer 2016 and March 2018, a period during which ex-tropical Cyclone Gita brought heavy rainfall to the region. Our full model included land cover, rainfall, topography and surficial geology. We determined the relative importance of each parameter included in the model, dropped parameters that failed to improve model performance, and from the final simplified model produced a high resolution (10 m x 10 m) landslide susceptibility surface for the Tasman region. In addition, we compared the accuracy of the ESC framework used in the NES-PF with our preferred model. We also explored the implications of increasing permanent forest cover and halting the clear-fell harvest of plantation forest to determine whether these management interventions might reduce landslide susceptibility in the study area.

Methods

Study site

The study was undertaken in a ~196 km² area located in the Tasman region of New Zealand. The area is subject to frequent extreme weather events with disruption caused by heavy rain and flooding (Macara 2016). The area includes Motueka, Riwaka and Marahau townships, flat land used for horticulture, grazing and rural-residential properties. It also includes the eastern flanks of the Mount Arthur Range on the western side of the Motueka River - an area dominated by steep terrain underlain by weathered granite and Riwaka Complex volcanic and metamorphic rocks. The predominant land cover is regenerating native forest interspersed with plantation pine (*Pinus radiata* D.Don) forest and some upland grazing (Cao et al. 2009; Young et al. 2005). Small farms and lifestyle blocks are scattered on the lower slopes and on alluvial soils next to the Motueka River.

The study area was delimited to include the catchments most affected by landslides that occurred during the period when ex-tropical Cyclone Gita passed over the Tasman region on 20 & 21 February 2018, and to include the area covered by aerial imagery acquired on behalf of the Tasman District Council to document the extent of landslides and flooding after the event (Figure 1).

Mapping landslides and land cover

Three aerial imagery datasets covering the study area were used in our analysis. These were acquired in 2012–2013, 2015–2016 and on 9 March 2018. The 2012–2013 and 2015–2016 datasets were sourced from the Land Information New Zealand (LINZ) data service (<https://data.linz.govt.nz/>) and had a resolution of 0.4 m Ground Sampling Distance (GSD). The March 2018 dataset (Figure 1) was sourced from the Tasman District Council and had a resolution of 0.3 m GSD. The earlier two datasets were used to identify landslides that existed prior to 2016 and to determine changes in land cover, especially the identification of areas of clear-felled plantation forest (CfPF) <8 years post-harvest. The March 2018 dataset was used to identify landslides that occurred between 2016 and 2018, and to determine land cover status at the time ex-tropical Cyclone Gita passed over the study area in February 2018.

Landslides identified in the March 2018 dataset, but not in earlier datasets, were digitised in Arcview 3.2 (Esri 1999) by drawing detailed polygons (mean vertex distance ~6 m) around landslide scars at the boundary between bare earth and vegetation. Debris fields were excluded from polygons delineating landslides. In total, 4,719 landslides were identified in the study area. These ranged in size from 0.001–1.2 ha and covered ~179 ha.

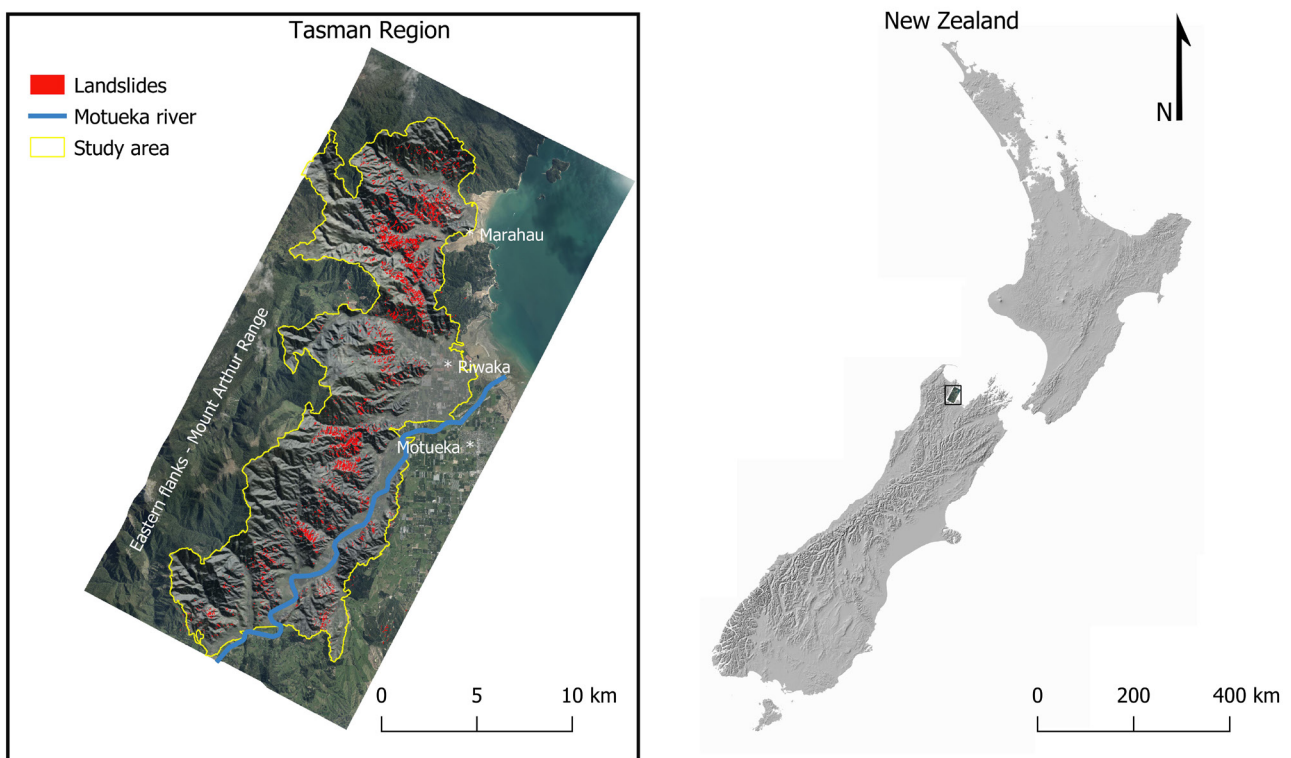


FIGURE 1: The left-hand panel shows the study area, digitised landslides, and the March 2018 imagery dataset used to digitise landslides and land cover classes. The right-hand map shows the location of the study area and the Tasman region of New Zealand.

Following a similar process to that used to digitise landslides, eight land-cover classes (Table 1) were identified and delimited by drawing detailed polygons (mean vertex distance ~6 m) around the boundary between land cover classes. In total, 756 land cover polygons were digitised within the study area.

TABLE 1: Landcover classes and abbreviations used.

Land cover class	Abbreviation
Bare ground other than landslides	Bgr
Clear-felled plantation forest c. 0-7 years after harvest	CfPF
Closed canopy plantation forest c. 8-30 years after planting	CCPF
Easy lowland pasture, horticulture and residential	EP&R
Hill pasture	HP
Mixed exotic woodland including small stands of exotic hardwoods	MxdW
Seral native vegetation	SNV
Tall native forest	TNF

Other spatial layers used

A 15 m DEM (digital elevation model) for the Tasman region (Columbus et al. 2011) was sourced from the LINZ data service (<https://data.linz.govt.nz/>). A 48 hour accumulated rainfall surface (0.5° resolution) covering 20 to 21 February 2018 was sourced from the National Institute of Water and Atmosphere (NIWA). Shape files of surficial geology rock types (Newsome et al. 2008) as classified by Lynn and Crippen (1991) and the ESC data layer used for the NES-PF were sourced from the Land Resources Information System (LRIS) portal (<https://lris.scinfo.org.nz/>). From the 15 m DEM additional gridded surfaces of aspect, mid-slope position index (MPI) (0 = mid-slope, 1 = maximum vertical distance up-slope and down-slope of the mid-slope position) (Dietrich & Böhner 2008), slope (°), and a 7-class topographical position index (TPI) (Guisan et al. 1999) were created in the geospatial software package SAGA (Conrad et al. 2015).

Data preparation

All spatial datasets (Figure 2) were imported into the statistical package R (R Core Team 2019), clipped to the study area extent and resampled to a standard 10 m x 10 m grid using the package raster (Hijmans et al.

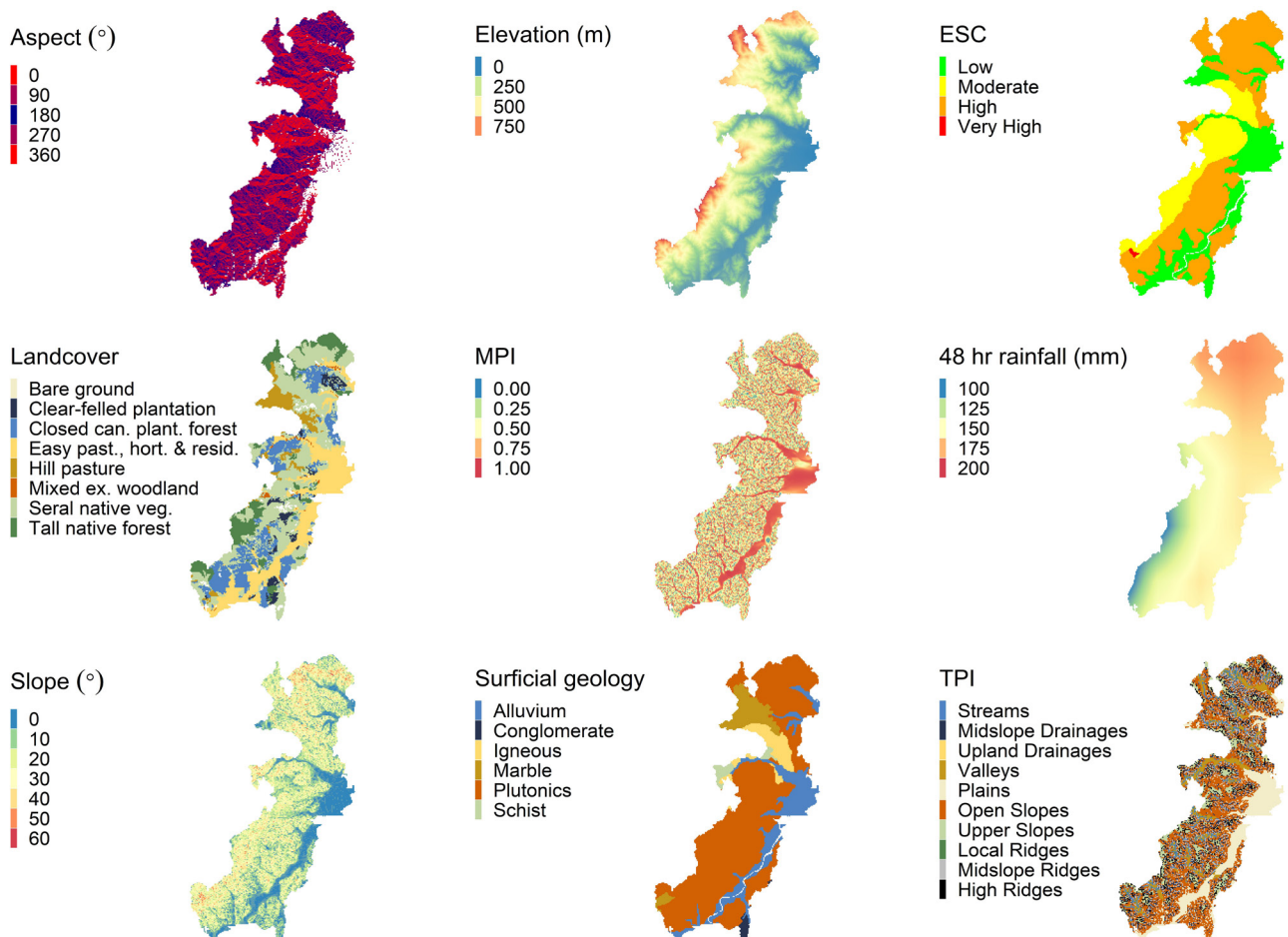


FIGURE 2: Gridded 10 m x 10 m resolution surfaces used for modelling landslides in Tasman, New Zealand. Abbreviated surface titles are erosion susceptibility classification (ESC), mid-slope position index (MPI), and topographical position index (TPI).

2016). The gridded landslide surface was converted to a spatial points data frame in which points designated as landslides had a value of 1 and non-landslide points had a value of 0. Using the raster::extract function, data from all gridded surfaces were joined to spatial landslide/non-landslide points, which were balanced by randomly reducing the number of non-landslide points from 1,989,804 to 20,987 to match the number of landslide points. The resulting dataset was split at random using the package groupdata2 (Olsen 2019) into a model training dataset comprising ~ 75% of the data and a model validation dataset comprising the remaining ~ 25% of the data. To ensure the training and validation datasets were independent we set the groupdata2:id_col parameter to "LandslideID" so that data points representing a landslide were either included in the training dataset or the validation dataset, but not in both.

Statistical analysis

Using the model training dataset, the binary response landslide/non-landslide was modelled as a function of aspect, elevation, MPI, land cover, rainfall, slope, surficial geology, and TPI using boosted regression trees (BRT) in the package dismo (Elith & Leathwick 2017; Hijmans et al. 2017). Tree complexity was set at 5, learning rate at 0.05 and bag fraction at 0.75 as recommended by Elith and Leathwick (2017).

After fitting the initial cross-validated model, the function dismo::gbm.simplify was used to determine if any variables included in the full BRT model failed

to improve performance. This process supported the inclusion of all model parameters except surficial geology, which did not improve model performance and was dropped. A simplified BRT model was then fit using all remaining parameters, and predictions from the resulting model derived for the validation dataset. Model accuracy was assessed using the area under the receiver operating curve (AUROC) (Fawcett 2006) and a confusion matrix (Kuhn 2008).

Following model simplification and validation the functions dismo::gbm.interactions and dismo::gbm.perspec were used to identify and visualise significant pairwise interactions between predictors. We also created 10 m x 10 m gridded landslide probability surfaces of the simplified model and a hypothetical afforestation scenario in which seral native vegetation (SNV) is replaced by tall native forest (TNF) and CfPF is replaced by closed canopy plantation forest (CCPF). The later was achieved by reclassifying grid cells classed as SNV to TNF and CfPF to CCPF prior to calculating model predictions for each 10 m x 10 m grid cell. From the landslide probability surfaces we calculated the extent of each land cover class with a predicted probability of landslides > 75% (Table 2).

In a separate process we modelled landslides in the training dataset as a function of ESC class using BRTs with the same tree complexity, learning rate and bag fraction settings described above. Model accuracy was assessed using AUROC and a confusion matrix.

TABLE 2: Landslide probability by: A. land cover class; and B. alternative land cover class. High probability = predicted probability of landslides > 75%.

A				B		
Land cover class	Total area (ha)	High landslide probability area (ha)	High landslide probability area / total area (%)	Alternative land cover class	High landslide probability area (ha)	High landslide probability area / total area (%)
Bare ground	23.6	1.7	7.3	No change	1.7	7.3
Clear-felled plantation forest	712.6	321.9	45.2	Closed canopy plantation forest	50.6	7.1
Closed canopy plantation forest	3511.6	227.9	6.4	No change	227.9	6.4
Easy pasture & residential	4223.8	21	0.5	No change	21	0.5
Hill pasture	1166.6	36.9	3.2	No change	36.9	3.2
Mixed woodland	149.2	2.1	1.4	No change	2.1	1.4
Seral native vegetation	7594.0	1266.3	16.7	Tall native forest	73.3	1
Tall native forest	2208.3	9.3	0.4	No change	9.3	0.4
All	19589.6	1887.1	10.1	All	422.8	3.4

Results

The simplified BRT model fit the training data well (AUROC = 0.94) and accurately predicted the presence and absence of landslides in the validation dataset (AUROC = 0.93; Accuracy = 0.867, +/- 95% CI = 0.0066, $p < 0.005$; Kappa = 0.73). Of the variables included in the model, land cover, elevation, rainfall, slope and aspect were most informative, with the land cover classes clear-felled plantation forest (CfPF) predicting the highest probability of landslides and tall native forest (TNF) predicting the lowest probability of landslides. Fitted functions for the continuous variables elevation, rainfall, slope and aspect indicated that the probability of landslides was highest at sites where > 130 mm of rain fell in 48 hours, elevation was < 500 m, slope was > 30°, and at sites with a north-easterly aspect (Figure 3). Fitted functions for the TPI and MPI indicated that landslide occurrence was highest on mid-slope and upper-slope drainages, but these parameters explained substantially less deviance in the response and had low importance scores (Figure 3).

Assessment of pairwise interactions between predictors revealed strong interactions between rainfall and aspect and rainfall and elevation. The nature of these interactions indicates that where high rainfall occurred in combination with north-easterly aspect and elevations < 500 m landslide occurrence was much more likely than if the effects of rain, aspect and elevation were simply additive (Figure 4). In contrast, interactions between rainfall and slope, TPI and MPI were weak.

Model predictions for current land cover indicate that the terrain most susceptible to landslides is concentrated toward the northern end of the study site on slopes

surrounding the settlements of Riwaka and Marahau (Figure 5). This area is dominated by vulnerable land cover classes seral native vegetation (SNV) and CfPF and received the highest total rainfall during the 48 hour period ex-tropical Cyclone Gita crossed the top of the South Island of New Zealand (Figure 2).

Model predictions highlight the susceptibility of SNV and CfPF to landslides, with ~17% and ~45% of the area occupied by these land cover classes assigned a predicted probability of landslides > 75% (Table 2). A hypothetical afforestation scenario in which SNV is converted to TNF and CfPF to CCPF shows that the high landslide probability area could be reduced by an estimated 1193 ha if SNV succeeds to TNF and a further 271 ha by halting clear-fell harvest of plantation forests (Table 2 & Figure 5). In combination, these changes could reduce the high landslide probability area within the study area from an estimated 1,887 ha to 423 ha (Table 2 & Figure 5).

Unlike the simplified BRT model presented above, we found the ESC was a poor predictor of landslides in the training (AUROC = 0.66) and validation datasets (AUROC = 0.65; Accuracy = 0.63, +/- 95% CI = 0.0093, $p < 0.005$; Kappa = 0.25). The marginal effect estimates for ESC classes low, moderate and high were 0.11, 0.28 and 0.29 respectively and increased in a stepwise manner as expected. However, the difference between the marginal effects for ESC classes moderate and high were negligible, and the marginal effect estimate for the ESC class very high was strongly negative (-0.68). However, the latter should be viewed with some caution as only 43.3 ha of the study area was assigned a very high ESC classification.

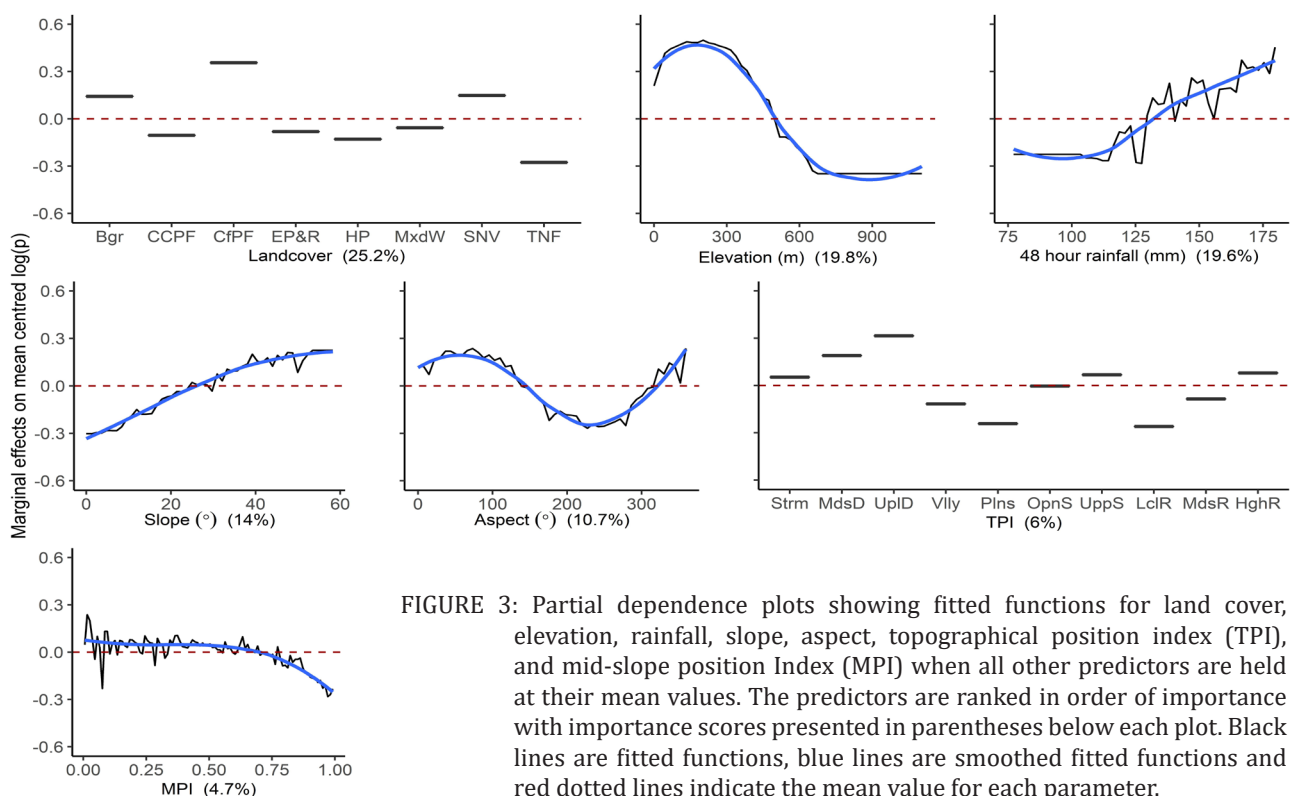


FIGURE 3: Partial dependence plots showing fitted functions for land cover, elevation, rainfall, slope, aspect, topographical position index (TPI), and mid-slope position Index (MPI) when all other predictors are held at their mean values. The predictors are ranked in order of importance with importance scores presented in parentheses below each plot. Black lines are fitted functions, blue lines are smoothed fitted functions and red dotted lines indicate the mean value for each parameter.

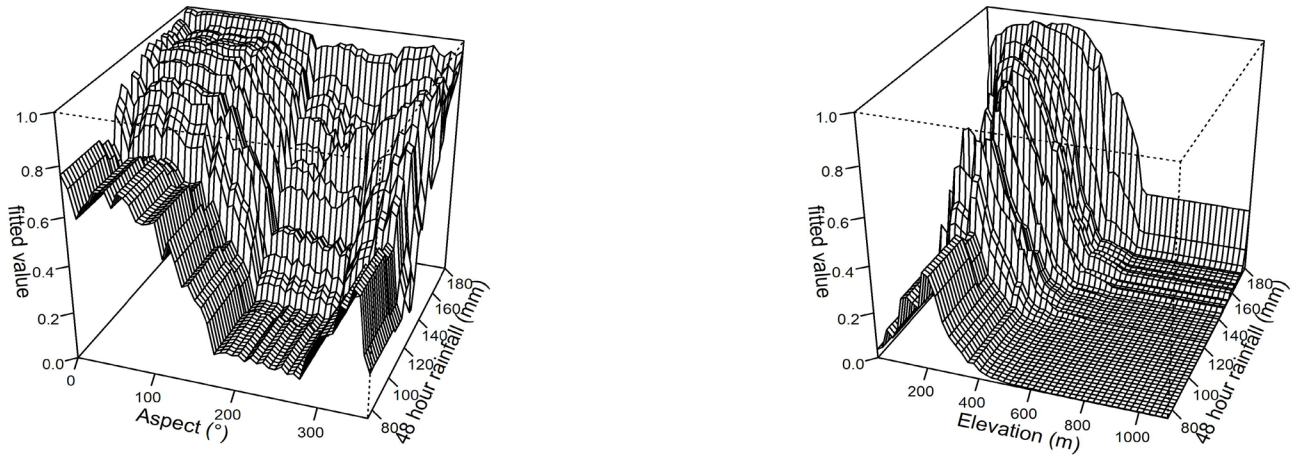


FIGURE 4: Three-dimensional partial dependence plots showing interactions between 48 hour rainfall (mm) and aspect (°) and 48 hour rainfall (mm) and elevation (m). All other variables are held at their mean values.

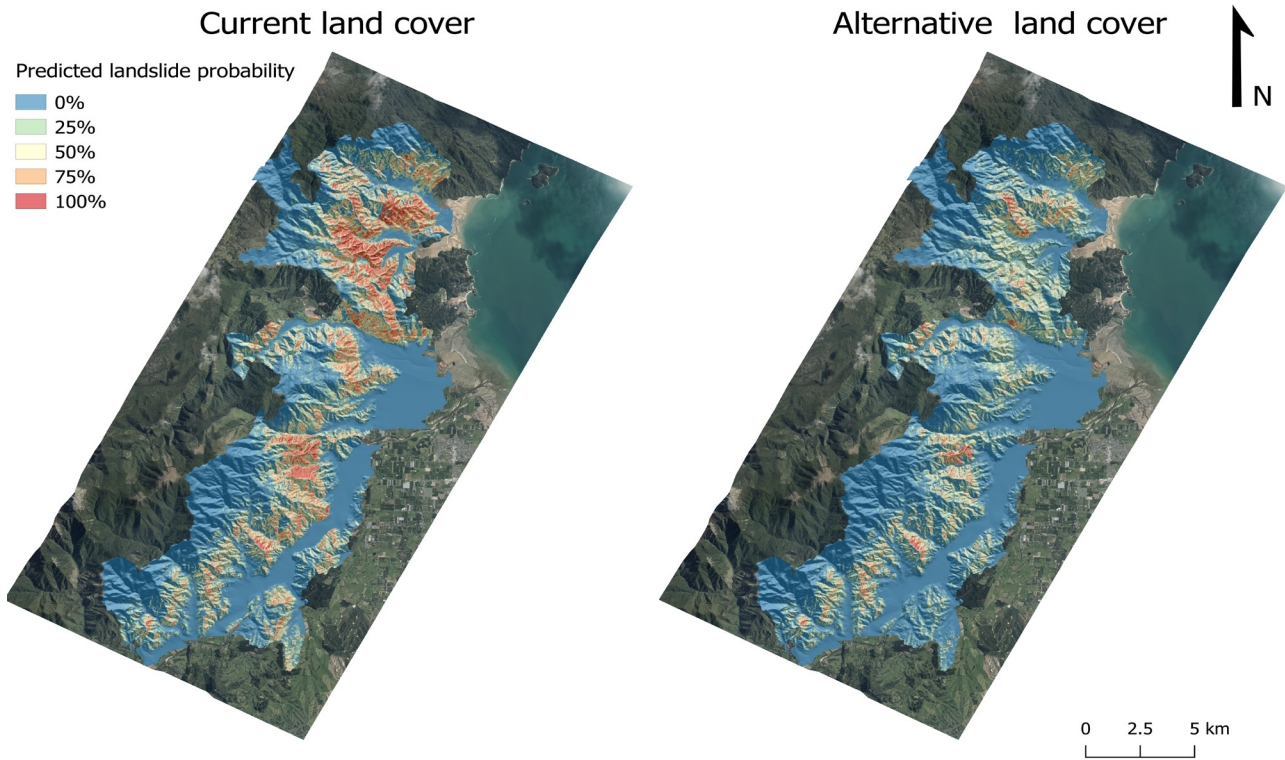


FIGURE 5: Modelled probability of landslides across the study under land cover described from March 2018 imagery (left panel), and modelled probability of landslides under an alternative management scenario in which areas of clear-felled plantation forest and seral native vegetation are converted to closed canopy plantation forest and tall native forest respectively (right panel).

Discussion

In our study, high resolution (10 x 10 m) gridded rainfall, topography, land cover surfaces were used to model landslides in the Tasman region of New Zealand. Our results are broadly consistent with the literature and reinforce the relevance of land cover, rainfall and topography as predictors of landslides but, most importantly, imply that effective land use management could substantially

reduce landslide occurrence in Tasman, New Zealand. In particular, our model suggests that increasing the extent of permanent forest cover and limiting clear-fell harvest of plantation forests on landslide-prone slopes could substantially reduce landslide occurrence during high-intensity rainfall events. The findings presented here are a first for the Tasman region, and provide an important resource for land managers.

Seral native vegetation and landslide occurrence

Seral native vegetation (SNV) is the dominant land cover in the study area and includes 1266.3 ha with a predicted probability of landslides > 75% (Table 2). In the Tasman region, SNV mainly comprises shallow rooted native species, such as five finger (*Pseudopanax arboreus* (Murray) Philipson), karamu (*Coprosma robusta* Raoul) and kahuhu (*Pittosporum tenuifolium* Sol. ex Gaertn.), which have low root-wood tensile strength (Watson & Mardern 2004) and occupy steep slopes on marginal farmland that was retired in the mid 1980's (Basher 2013; Cao et al. 2009). Our study indicates SNV is more vulnerable to landslides than tall forest, and is consistent with other studies (Dymond et al. 2006; D.L. Hicks 1991; Marden & Rowan 1993) that document higher landslide occurrence in areas of seral or immature vegetation cover. Thus, if SNV reverts to tall native forest (TNF) through natural succession, landslide occurrence in the Tasman region is likely to decrease. Here, we estimate the area with a predicted probability of landslides > 75% could be reduced by as much as 1193 ha if TNF were to fully replace SNV (Table 2).

To accelerate the transition from SNV to TNF, land management agencies could control factors that retard natural succession, such as animal browse by goats, possums, deer and domestic stock (D.A. Wardle et al. 2001); land clearance (Johnson & Gerbeaux 2004); and fire (Fill et al. 2015). Under-planting or seed sowing could also be employed to overcome seed limitation of native forest canopy species (Coomes et al. 2003; McAlpine et al. 2016), such as New Zealand beech (*Fuscospora and Lophozonia* spp. (Hook.f.) Heenan et Smissen), which are poor dispersers and unlikely to recolonise some areas without assistance (J. Wardle 1984).

Clear-fell plantation harvest and landslide occurrence

Clear-felled plantation forest (CfPF), which includes areas where trees have been replanted after harvest but are <8 years old, occupies only 712.6 ha of the study area. However, ~ 45% of this area has a predicted probability of landslides > 75% (Table 2) indicating CfPF is much more vulnerable to landslides than other land cover classes and contributes disproportionately to landslide occurrence. This is consistent with studies conducted elsewhere in New Zealand (e.g. Dymond et al. 2006; Glade 2003; Marden & Rowan 1993, 2015; Page et al. 1994; 2000) that highlight the vulnerability deforested steeplands to landslides and sediment loss, but also show replanted plantation forest can be associated with high landslide occurrence for up to 8 years after replanting (Marden & Rowan 1993).

Approximately 40% of New Zealand's production plantation forests are grown on steep, erosion-prone hillslopes due to lower land prices and higher return on investment, and in some areas were established to stabilise erodible terrain (Visser et al. 2018). Preferred harvesting methods involve large-scale clear-felling paired with ground-based or skyline cable log extraction to maximise cost efficiencies (Visser et al. 2018). Harvesting often occurs across entire catchments and

can cause considerable soil disturbance and reduce slope stability (Marden & Rowan 1993; Marden et al. 2006); increase surface water yields and velocity (Bosch & Hewlett 1982; Davie & Fahey 2005; Rowe & Pearce 1994); and increase sediment and debris flows (Fahey & Coker 1992; Gibbs & Woodward 2017, 2018; D.M. Hicks et al. 2008; O'Loughlin 1994). Collectively, these factors can result in significant damage to downslope property and infrastructure and freshwater and marine environments during large storm events (Ryan et al. 2008; Thrush et al. 2004; Visser et al. 2018).

Some authors have argued the environmental impacts of forestry could be reduced by implementing stringent clear-felling limits on erosion prone lands, or by implementing alternative low impact harvesting methods such as patch-cutting or single tree selection (e.g. Amishev et al. 2014; Visser et al. 2018). Our model indicates closed canopy plantation forest (CCPF) had a much lower probability of landslides than CfPF, and implies harvesting protocols that leave a greater proportion of CCPF standing would reduce landslide occurrence. However, the area of CfPF with a predicted probability of landslides > 75 % could be reduced by an estimated 271 ha if all plantation forest in the study area was managed as permanent CCPF (Table 2). Additional reductions in landslide occurrence may also be possible if CCPF was converted to TNF, which had a lower probability of landslides than other cover classes included in our model; this conversion might be accelerated by underplanting native podocarp species (Forbes et al. 2016).

Lower landslide occurrence in native forest than in plantation forest is also reported by D.L. Hicks (1991), but others record little or no difference between native and exotic forests (Hancox & Wright 2005; Marden & Rowan 1993), and Marden and Rowan (2015) report higher sediment generation rates for native forest than mature exotic forest. In part, discrepancies in reported erosion rates for native and exotic forests may be explained by inconsistent classifications of native and exotic forests (e.g. Hancox & Wright 2005; D.L. Hicks 1991; Marden & Rowan 1993), but also because interactions between rainfall, topography and land cover, although acknowledged, are not addressed by the analytical approaches used (e.g. Hancox & Wright 2005; Marden & Rowan 1993, 2015). Nevertheless, there is broad consensus in the literature that mature forest reduces landslide susceptibility and that low impact harvesting methods or other initiatives that result in increased forest cover on erodible lands ought to result in improved environmental outcomes.

The National Environmental Standards for Plantation Forestry (NES-PF) is the principal legislative instrument for managing plantation forestry activities in New Zealand and prescribes rules for specified activities based on the erosion susceptibility classification (ESC) of the land on which they occur. However, in our study the ESC failed to reliably discriminate areas of high landslide occurrence from areas of low landslide occurrence. This probably relates to the resolution of the ESC and the New Zealand Land Resource Inventory (NZLRI) (Newsome

et al. 2008) on which it is based, as the scale (1:50000) of these data layers may be too coarse to adequately represent local scale (1:10000) variation in land cover, climate, or topography. Deficiencies in the ESC could also be due the quality of the data contained in the NZLRI, which in some areas is 40 years out of date (Bloomberg et al. 2011). The potential shortcomings of the ESC are well recognised (Basher et al. 2015a; Bloomberg et al. 2011; Marden et al. 2015) and it was intended as a regional rather than local land use management tool (Bloomberg et al. 2011). Nevertheless, the failure of the ESC to discriminate areas of high landslide occurrence from areas of low landslide occurrence in our study area, which covers almost 20,000 ha, raises questions about the reliability of the ESC as a regional land management tool in Tasman, New Zealand, and may warrant investigation elsewhere.

Spatial rainfall pattern

In our study, we included a 48 hour rainfall parameter which was informative and interacted with aspect and elevation. We suspect interactions between rainfall and topography are due to the prevailing north-easterly wind direction during Gita focusing rainfall on north-eastern slopes, with more precipitation occurring at low elevations (< 500 m) in the northern sector of the study area due to the moist air mass condensing as it cooled travelling upslope over the coastal hills. Fine scale variation in rainfall is not evident in the rainfall surface used (Figure 2), but the importance of aspect and elevation in the model and the complex nature of their interactions suggest that these two parameters may explain fine scale variation in rainfall that is not inherent in the rainfall surface used. Alternatively, the importance of aspect in the model may relate to differences in vegetation between northern and southern facing slopes, and the importance of elevation may reflect upslope watershed area, although we would have expected the mid-slope position index (MPI) to have been a better proxy for upslope watershed area than elevation. Irrespective of the exact nature of the relationships between rainfall and topography, however, these findings imply that spatial patterns of high intensity rainfall, where it is predictable at local scales, could improve landslide susceptibility modelling. Heavy rainfall in the Tasman region generally comes from the north-east (Macara 2016); thus, it is likely that future landslides in the study area will occur more frequently on north-eastern slopes at low elevation.

Frequency and magnitude of landslide triggering events

Major multiple-landslide events in New Zealand are often associated with either heavy rainfall or earthquakes. The 2016 Kaikoura earthquake occurred during the period covered by our landslide analysis, and caused thousands of landslides in the seaward Kaikoura ranges and along the east coast (Massey et al. 2018). This event was extremely well-documented, and landslides generally occurred within 10 km of fault surface ruptures (Massey et al. 2018). There are no known active faults within the

study area (GNS 2019 active faults database), and the landslides documented in our study are >100 km from areas that experienced shaking greater than magnitude 3 in the 2016 Kaikoura earthquake (Hamling et al. 2017). We thus consider it extremely unlikely than any of the landslides in our dataset resulted from seismic triggers. While earthquake-triggered landslides have been the focus of much study in recent years, landslides are more likely to be triggered by rainfall (e.g. Dellow 2010). Storms similar in size to Cyclone Gita are a relatively frequent occurrence in NZ. Between 1970 and 1997, tropical cyclones hit NZ a little more than once a year on average (Sinclair 2002), and storms with a similar intensity of precipitation (>130 mm in 24 hours) occur every 1-5 years in study area (Tasman District Council; recurrence estimates drawn from 1962-2019 from Takaka Hill, Riwaka South, and Motueka at Woodmans rain gauges). Climate change is likely to increase the frequency and intensity of major storms (IPCC 2018) and rainfall-triggered landslides (Crozier 2010). In a warming world, high-resolution landslide susceptibility models that enable land managers to make informed decisions about land use and regulation at a scale relevant to land use activities will become increasingly important.

Conclusions

Our study shows that accurate, high-resolution landslide probability surfaces can be developed from landslide distribution, land cover, topographical and rainfall data layers. Our model suggests that land cover is the most important determinant of landslide occurrence during large rainfall events in the Tasman region, and that landslide susceptibility could be substantially reduced by increasing the extent of permanent forest cover and limiting clear-fell harvest of plantation forests on landslide-prone slopes. This work highlights the importance of reliable erosion susceptibility surfaces that allow land managers to accurately identify areas of high landslide susceptibility at the scale at which land use activities occur.

Reducing landslides and associated erosion will improve the health of freshwater and near shore marine ecosystems and reduce future social and economic costs of large storm events. With increases in the size and frequency of large storm events predicted under future climate scenarios, progress on reducing landslide susceptibility is urgent.

Competing interests

The authors declare they have no competing interests.

Authors' contributions

RM initiated the study and created the digitised landslide and land cover data-layers used. JG led the writing, performed the statistical modelling and produced all figures. CL made a significant contribution to writing and provided geomorphological expertise. All authors read, critiqued, and approved the final manuscript.

Acknowledgements

We thank Susan Timmins, Clayson Howell, Kevin Norton and three anonymous reviewers who provided helpful critique and advice on the manuscript. We also thank Martin Doyle and Pete Frew from Tasman District Council who provided rainfall data and aerial imagery for the study area, and Andrew Tait from NIWA who created the modelled 48-hour rainfall surface used.

Availability of data and materials

Please contact the corresponding author for data requests.

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