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QUANTIFYING THE EFFECT OF TREES ON LANDSLIDE EROSION AND SEDIMENT DELIVERY AT FARM SCALE

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Introduction

The introduction of sediment standards into New Zealand's National Policy Statement for Freshwater Management (NPS-FM) has required regional authorities to manage freshwater in a way that considers the effects of land-use, including the effects on receiving estuarine environments (New Zealand Government 2020a). Managing suspended fine sediment in view of ecosystem health is a component of the NPS-FM, whereby monitoring of visual clarity at measurement sites is a mechanism used to determine outcomes.

Moreover, freshwater farm plans (FFP) have been established as a legal instrument under the Resource Management Act (RMAA sections 217A to 217M, New Zealand Government, 2020b) to identify environmental actions on farms in consideration of objectives for the catchment. Therefore, understanding the impact of erosion and sediment control is important to achieve the desired environmental outcomes and – more specifically – sediment standards. The RMAA suggests an FFP must provide clear (spatial) guidance on the risks with respect to freshwater. Furthermore, the impact of the actions must be measurable and quantifiable for auditing purposes.

In this context, silvopastoralism in New Zealand's highly erodible hill country is an important form of erosion and sediment-loss control (Van Kraayenoord and Hathaway 1986, Hathaway et al. 1987, Wilkinson 1999, Watson et al. 2000, Mackay-Smith et al. 2021). Space-planting poplars and willows to mitigate erosion is an erosion management technique that has been well documented (Phillips and Marden 2000, Basher et al. 2008, Phillips et al. 2008, Basher 2013). Despite a long history in improving sustainable land management and soil conservation, there has been relatively little quantitative work to establish the effectiveness of space-planted trees in reducing shallow landslides at farm to landscape scales.

We present research on quantifying the soil stability mitigation effectiveness of trees at farm scale using statistical modelling. In most existing statistical landslide susceptibility models, land use or land cover data (e.g., LCDB) are used to capture the varying effect of vegetation composition (Smith et al. 2021). Yet, these data are rarely available at the scale required to quantify the effect of individual trees across a silvopastoral landscape (Fig. 1).

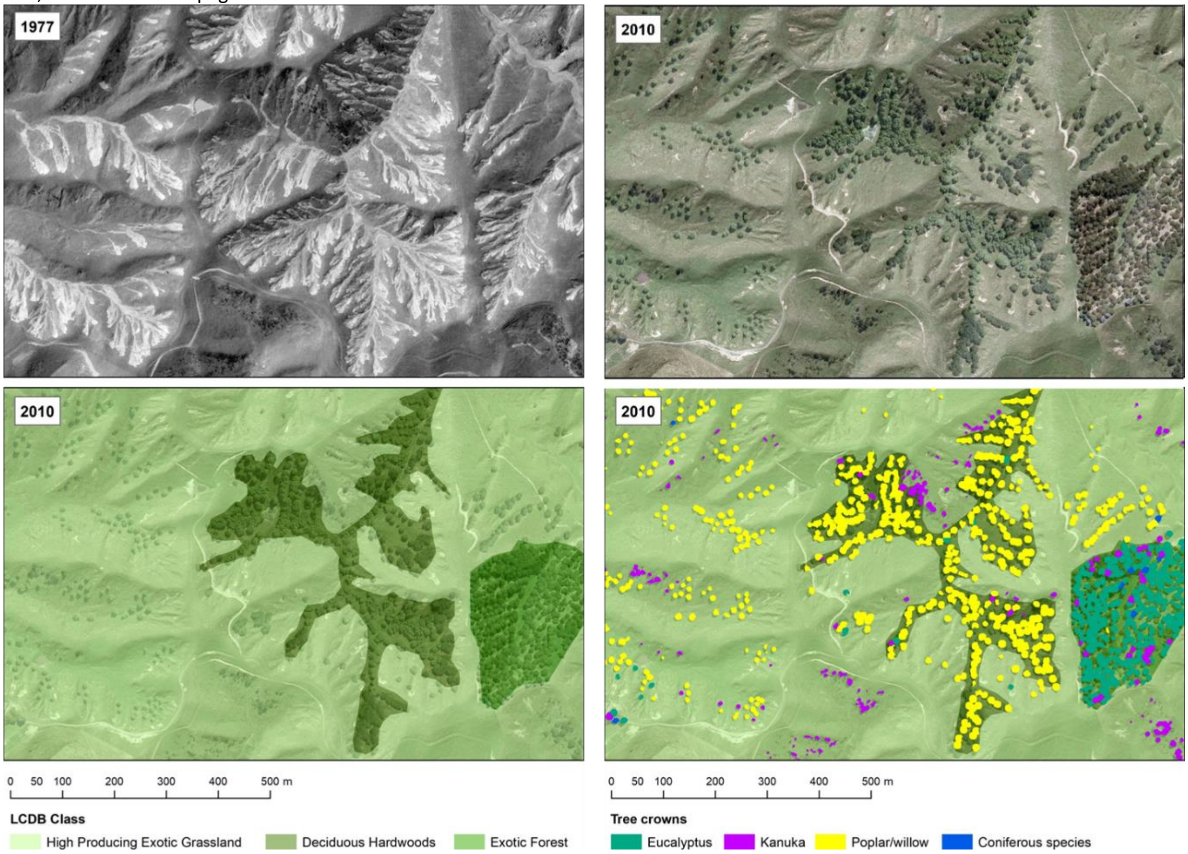

Figure 1. Many widely spaced poplars, willow and eucalyptus trees (top-right) have been planted on this farm in the Wairarapa in response to the devastating rainfall event of 1977 (shown in the historic aerial photo top-left). The Land Cover Data Base of New Zealand (LCDB; bottom-left) is not at the scale required to capture the effect of individual trees. LiDAR data enables individual trees to be identified and classified into their genera using high resolution imagery (bottom-right).

Methods

We addressed this data and knowledge gap by mapping and classifying trees using Light Detection and Ranging (LiDAR) data in combination with regional orthophotography (2010 – 2017) across an 840 km^2 study area in the Wairarapa (Spiekermann et al. 2021). Subsequently, a statistical landslide susceptibility model for pastoral hill country in the Wairarapa was developed, which for the first time includes individual trees of multiple genera (poplar/willow, eucalyptus, conifer, mānuka/kānuka). Other variables used in the logistic regression model include LiDAR-derived slope gradient and aspect, as well as rock type from the New Zealand Land Resource Inventory. The landslide susceptibility models were trained and tested using an inventory consisting of 43,000 landslide scars and an equal number of randomly selected non-landslide points (Spiekermann et al. 2022).

Finally, to enable biological mitigation to be targeted to sediment critical source areas, determinants of sediment connectivity were investigated for a landslide-triggering storm event in 1977 (Fig. 2; Spiekermann et al., *submitted*). In a first of its kind, a morphometric landslide connectivity model was developed using lasso logistic regression to predict the likelihood of sediment delivery to streams following landslide initiation.

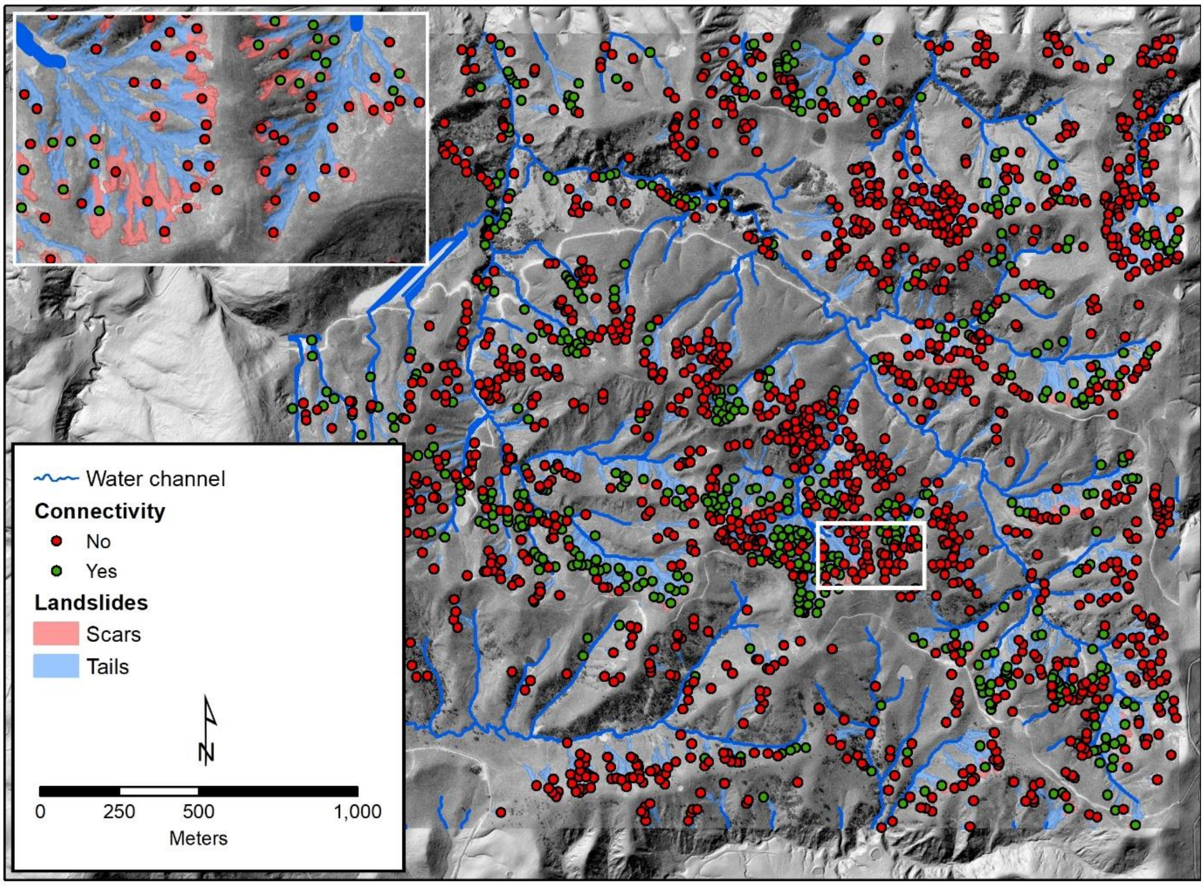

Figure 2. Development of a connectivity model using a set of 2000 scars and 1200 debris tails from the rainfall event of 1977 in a 700-ha study area in the Wairarapa. Connectivity was operationalized using a definition based on the intersection of debris tails and streams.

A modular approach combined spatial predictions of landslide susceptibility and connectivity at 1-m spatial resolution for 50 farms (>300 ha) in the Wairarapa hill country (Fig. 3). Using a treeless pasture scenario as the baseline, reductions in sediment delivery from shallow landslides to streams were quantified under the following three scenarios: 1) existing woody vegetation (WV), 2) targeted mitigation (S1) and 3) blanket space-planting using a 15 x 15 m grid of poplars (S2).

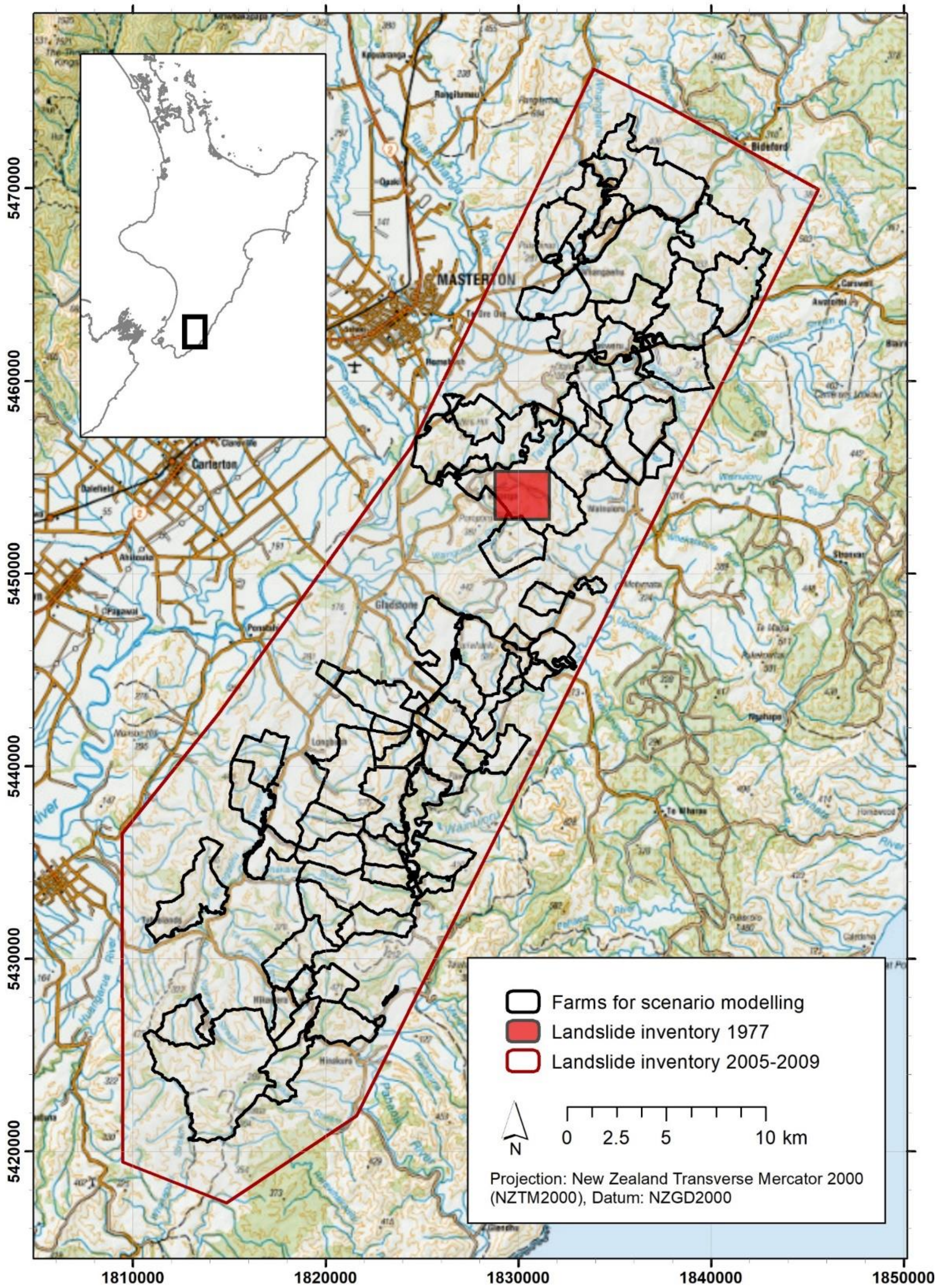

Figure 3. Location of study area of the 1977 landslide inventory used for the connectivity model, the extended study area of the 2005-09 landslide inventory used by the landslide susceptibility model, and the location of 50 farms selected for the land management scenarios.

Results

Landslide susceptibility

Spatial predictions in landslide susceptibility are illustrated for a small area in the Wairarapa (Fig. 4). It provides a contrast between the eucalyptus grove to the east, which has been planted on highly susceptible terrain, and the poplars and willows to the west, which are primarily located on lower slopes or valley bottom where landslides are unlikely to occur with or without the presence of trees. The effectiveness of individual trees in reducing landsliding was shown to be less a function of species than of targeting highly susceptible areas with adequate tree densities.

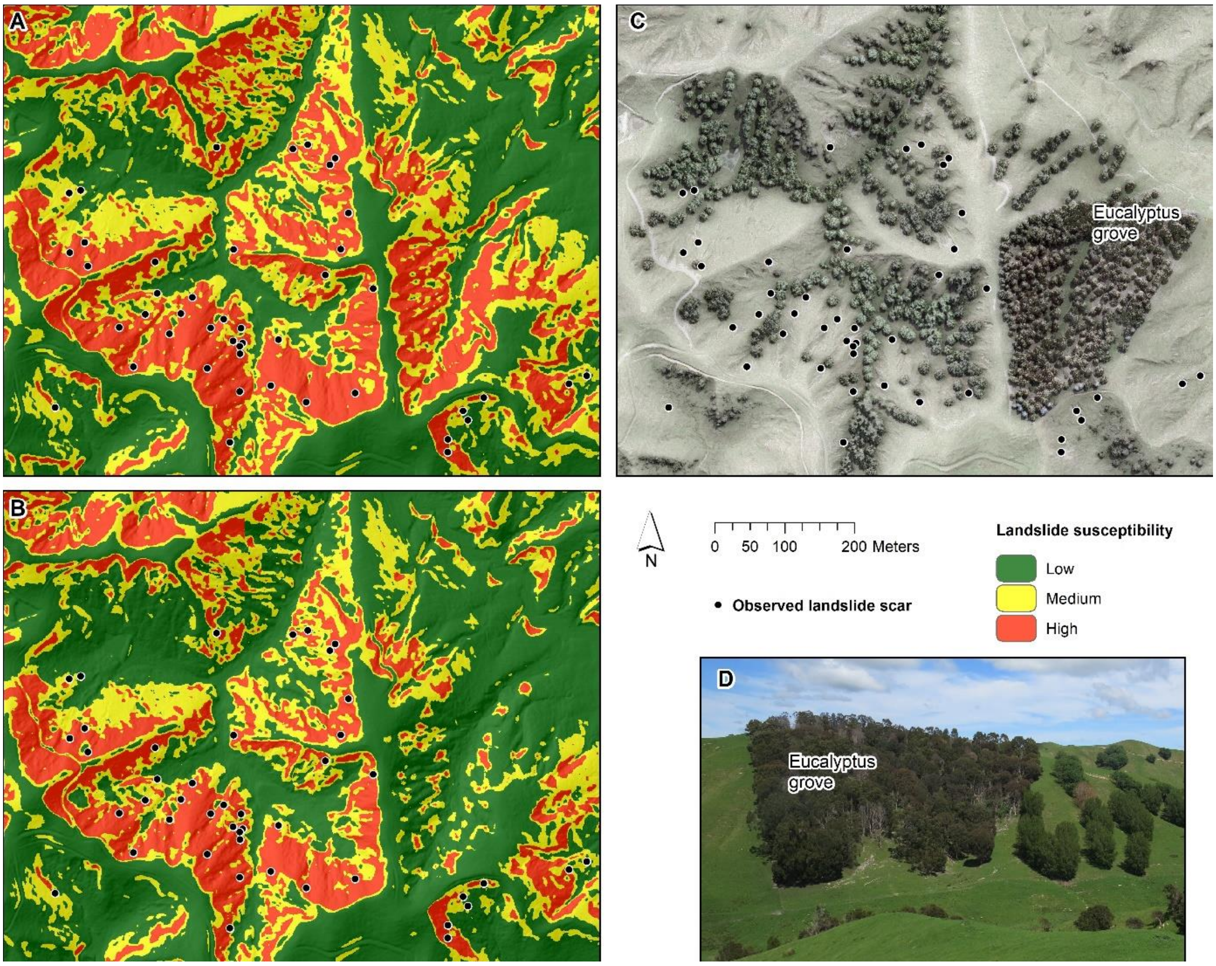

Figure 4. Spatial predictions of landslide susceptibility under A) tree-less pasture, B) actual trees present as shown in C). The photograph (D) of the eucalyptus grove seen in C) courtesy of Ebony Davison. The landslide susceptibility classes correspond to expected rates of landslide erosion based on past observations: 80% in the red zone; 15% in the yellow zone and 5% in the green zone.

Two farms were selected to illustrate application of the landslide susceptibility model at farm scale by quantifying the reduction in landsliding attributed to trees. Accounting for the rate of landslide erosion across these three different susceptibility classes, and assuming the triggering mechanism of observed landslides is the same in future, landslide erosion has been reduced by 16.6% at Farm 1 and 42.9% at Farm 2 due to all trees present on the farms (Fig. 5). We found that the area of highly susceptible slopes where the majority (80%) of landslides occur occupy just 12% and 7% of Farms 1 (1,700-ha) and 2 (462-ha), respectively. This suggests there is great potential for smarter targeting of erosion mitigation.

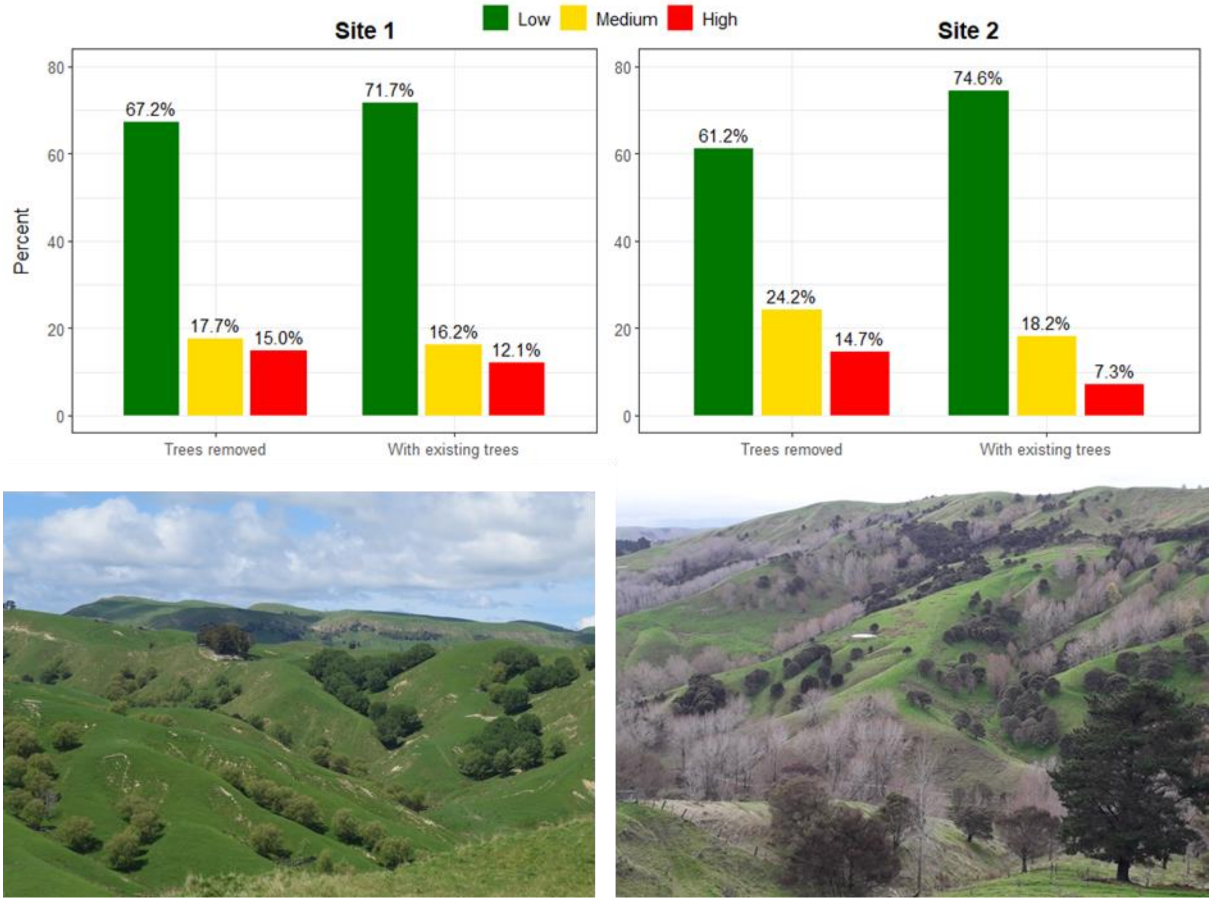

Figure 5. For two selected farms, the distribution of the landslide susceptibility classes under a) treeless pasture and b) actual existing trees. The change in the distribution amounts to a 17% reduction in landslide erosion at Site 1 and a 43% reduction at Site 2. The photos below provide a visual explanation for these differences: Site 1 has much lower tree densities than Site 2.

Landslide connectivity

The sediment delivery ratio to the stream network for the 1977 event was 0.21, equating to an event sediment yield of 3548 t km^{-2}. The likelihood of sediment delivery was greatly enhanced where debris tails coalesce. Besides scar size variables, overland flow distance and vertical distance to sink were the most important morphometric predictors of connectivity.

The landslide susceptibility and connectivity models were combined through in intersection of the three classes, creating nine classes. Tree planting on slopes (points and crosses show the location of individual trees) has reduced the likelihood of shallow landsliding and can mitigate sediment more effectively where the potential for sediment delivery is greatest (Fig. 5). The class "high" landslide susceptibility and "high" connectivity is not only where future landslides are most likely to be triggered, but also much more likely to delivery sediment to water ways (Fig. 5).

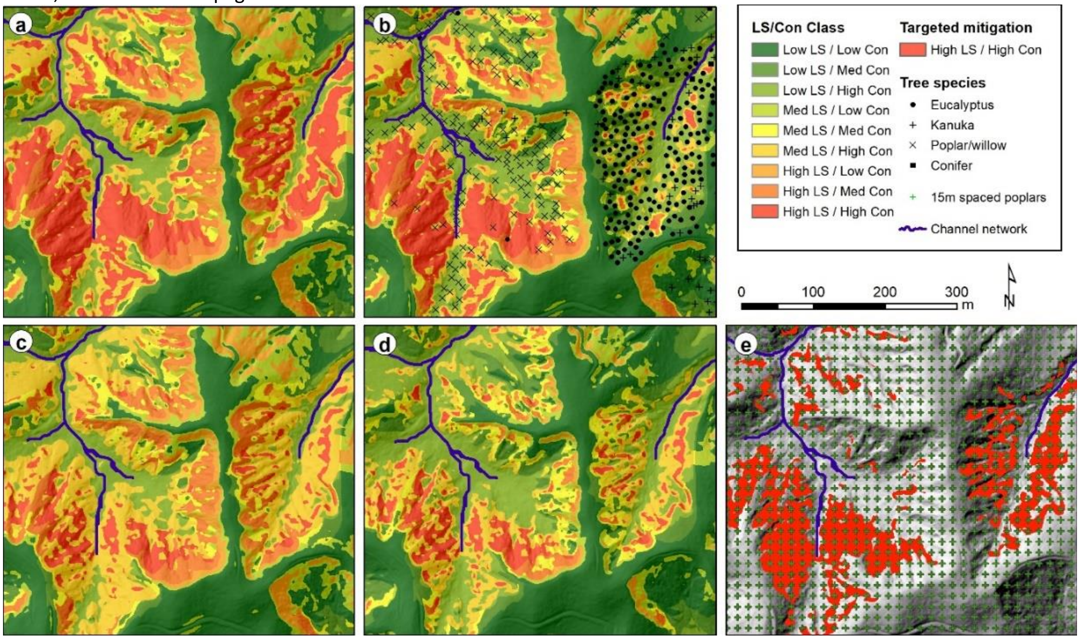

Figure 6. Coupled landslide susceptibility and connectivity classifications showing where landslides are most likely to be triggered (High LS) and deliver sediment to the stream network (High Con) under a) pasture, b) existing trees, c) targeted mitigation to terrain shown in e), and d) full tree cover using 15x15 m grid of poplar trees shown in e).

Land management scenarios

Results of scenario modelling across 50 farms (with a median farm size of 608 ha) suggests that, in total, only 6.6% of the pastoral land (2400 ha of 36,600 ha) is both highly susceptible to shallow landsliding and has high potential for sediment delivery to the stream network. However, due to the existing tree cover (WV), this class now represents just 4.6% of the total land area. The change in class distribution from a pasture only scenario (Fig. 6a) to that of 2013 (Fig. 6b) has led to an estimated reduction in sediment delivery of 23.8% across the 50 farms (Table 1).

Targeted mitigation of the 6.6% of highly susceptible and connected land using a 15x15 m grid of poplars (Fig. 6c, 6e) has potential to reduce sediment delivery by 33.2% compared with the baseline scenario. The maximum reduction in sediment delivery using the same 15 m-spaced trees covering all farmland is 56.1%. Under these scenarios, the sediment yield for the storm event of 1977 would have been reduced from 3548 t/km^2 (equivalent to the pasture-only scenario S_0) to 2703 t km^{-2} due to existing vegetation, 2356 t/km^2 for S_1 (targeted) and 1557 t km^{-2} for S_2 (maximum).

Cost-effective erosion and sediment mitigation

On average, just 3 trees/ha of farm are required to mitigate the 2400 ha of highly susceptible and connected terrain across the 50 farms. The median area of this zone requiring mitigation is 36 ha across the 50 farms, which would require an investment of approximately $53,000 per farm to achieve the median reduction in sediment delivery of 33.6%. Thus, the average investment required on a per hectare basis amounts to $2.82 to achieve a 1% reduction in sediment delivery from shallow landslides using a targeted approach to mitigation (Fig. 7). For example, if a 10% reduction is desired (compared to the treeless baseline) for a 500-ha farm, the investment would amount to $14,100 – assuming all trees survive.

This compares to S_2, which represents a random approach to targeting, i.e., mitigation is implemented proportional to the area occupied by the landslide susceptibility/connectivity classes. The average investment to achieve a 1% reduction in sediment delivery is thus substantially greater ($26.2/ha; Fig. 7). To achieve a 10% reduction on the same farm using this non-targeted approach, an investment of approximately $131,000 would be required. There is thus an order of magnitude difference in terms of cost-effectiveness between a targeted versus non-targeted approach.

Table 1 Total reduction in sediment delivery to streams across 50 farms (35,900 ha) under different land management scenarios.

	Existing vegetation	Scenario 1	Scenario 2
Reduction (%)	23.8	33.6	56.1
Tree count	738,818	105,307	1,629,381
Area treated (ha)	12,480	2369	36,661
Farm-average trees/ha	20.2	2.9	44.4
Average cost for 1% reduction ($/ha)	na	2.82	26.2

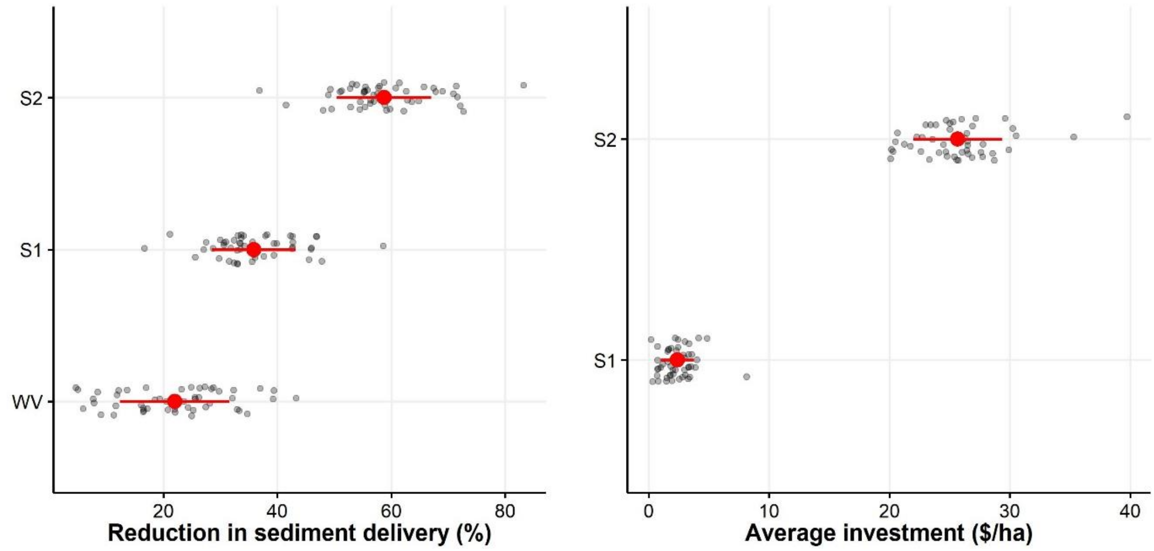

Figure 7. Insert a). Modelled reduction in sediment delivery to the stream network (%) for existing woody vegetation (WV), targeted mitigation (S1) and maximum possible with full tree cover (S2). Red strip charts correspond to mean of sediment reductions (point) from 50 farms and 1 SD (line); Insert b). The farm-average investment required on a per hectare basis to achieve a 1% reduction in sediment delivery.

Conclusion

The RMAA specifies that an FFP must “identify any adverse effects of activities carried out on the farm on freshwater and freshwater ecosystems” and “specify requirements that (i) are appropriate for the purpose of avoiding, remedying, or mitigating the adverse effects of those activities on freshwater and freshwater ecosystems; and (ii) are clear and measurable “(section 217F, RMAA). This research uses geospatial methods and statistical models to address these challenges related to erosion and sediment control in New Zealand’s pastoral hill country.

The results of this research demonstrate that LiDAR enables new higher-resolution data collection and analysis, including at the scale of individual trees. In a world-first, individual trees were included in a statistical landslide susceptibility model, resulting in greater accuracy and precision of spatial predictions. Landslide susceptibility provides a data-driven approach to erosion and sediment mitigation. The resulting high resolution maps can be used for mitigation planning at farm to catchment scale, and thus complement regional-scaled approaches to landslide susceptibility (Smith et al. 2021).

By coupling the landslide susceptibility and connectivity models, the effect of widely spaced trees in silvopastoral landscapes was quantified both in terms of soil-conserving and sediment-reducing properties. A major finding of this research is that future landslide-derived sediment source areas make up < 7% of the farmland in the Wairarapa hill country. Thus, not only can the resulting spatial predictions (maps) provide a means to target mitigation to areas where future shallow landslides are most likely to occur, but – perhaps more importantly – target future tree planting to locations that are likely to be future sources of fine sediment. Moreover, land management scenario modelling suggests targeted mitigation increases the cost-effectiveness of measures by an order of magnitude. In this way, the methods are both novel and have immediate relevance to support land management decisions aimed at creating a more sustainable socio-ecological landscape.

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