Shallow landslide susceptibility and connectivity to waterways

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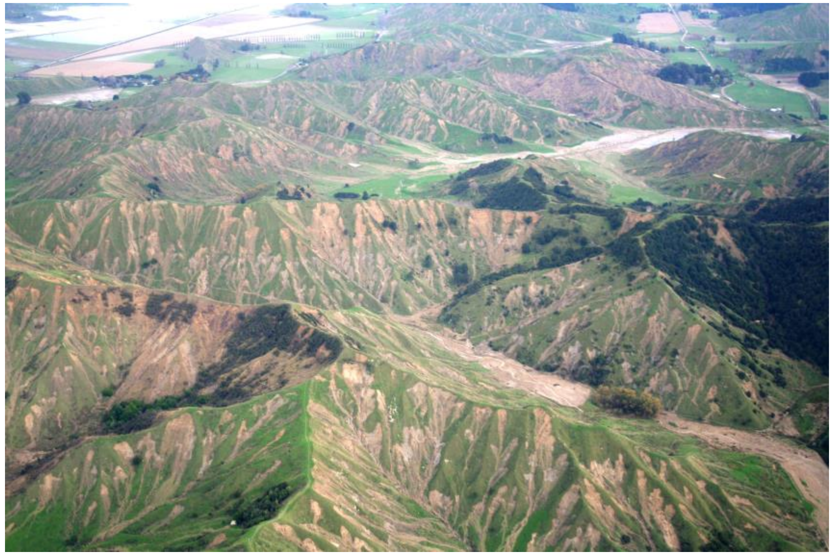
Outline

- Background
- Landslide susceptibility and connectivity – Methods
- Factors influencing landslide occurrence – Findings from research
- Tairāwhiti region shallow landslide susceptibility and connectivity layers
- Key messages

1.1 Background
– Shallow landslides in hill country

- Focus on rainfall-induced shallow landslides
- Rapid slides & flows – typical source areas 50-100 m^2 and depth < 1 m

- Hill country – elevation <1000 m, slopes ~20-30°
- Landslide erosion accelerated by past deforestation for pastoral farming
- Significant economic and environmental impacts – approx. NZ$ 250-300 M yr^{-1}



1.2 Background – Research timeline

Oct 2018 **Smarter Targeting of Erosion Control (STEC)** research programme commences - MBIE Endeavour Fund

– inform design and implementation of cost-effective, targeted erosion control measures to meet national water quality targets.

Jan-Feb 2023 Extreme weather events, incl. Cyclones Hale and Gabrielle

Aug 2023 Gisborne shallow landslide susceptibility layers shared freely as an output from STEC

Sep 2023 STEC programme ends

Mar 2024 Produced landslide connectivity layers for GDC

2. Landslide susceptibility and connectivity – Methods

2.1 What is landslide susceptibility?

- **Landslide susceptibility:** the spatial probability of future landslide occurrence given local environmental conditions
- Landslide susceptibility models use a **statistical** approach to quantify future land instability
- Susceptibility models predict **where** and not **when** (i.e. how frequently) landslides may occur.
- Landslide susceptibility modelling requires data:
  - ➢ Landslide source locations
  - ➢ Non-landslide locations
  - ➢ Spatial co-variates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Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Comparing methods of landslide data acquisition and susceptibility modelling: Examples from New Zealand

Hugh G. Smith *, Raphael Spiekermann, Harley Betts, Andrew J. Neverman

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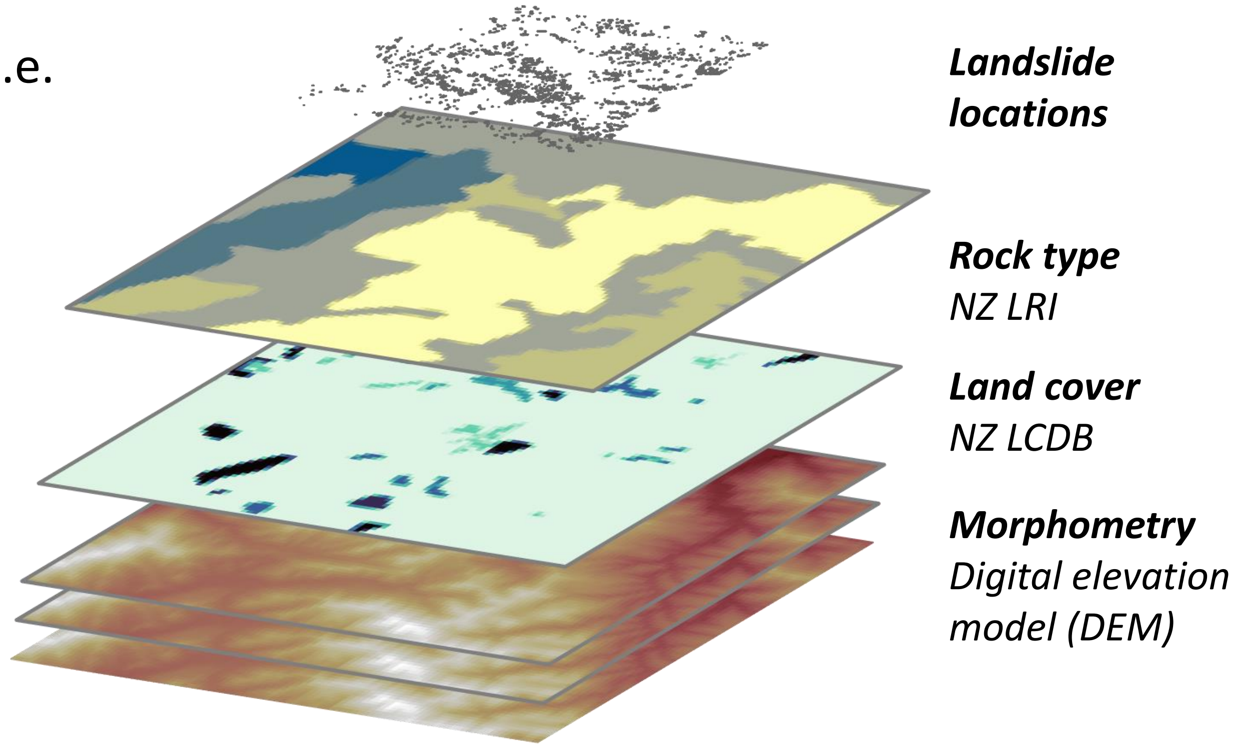
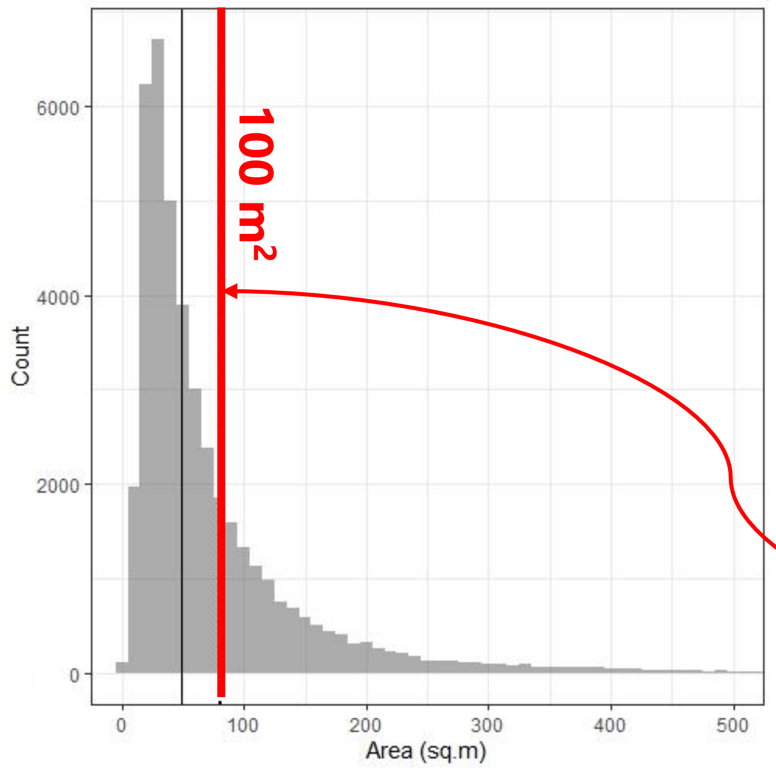


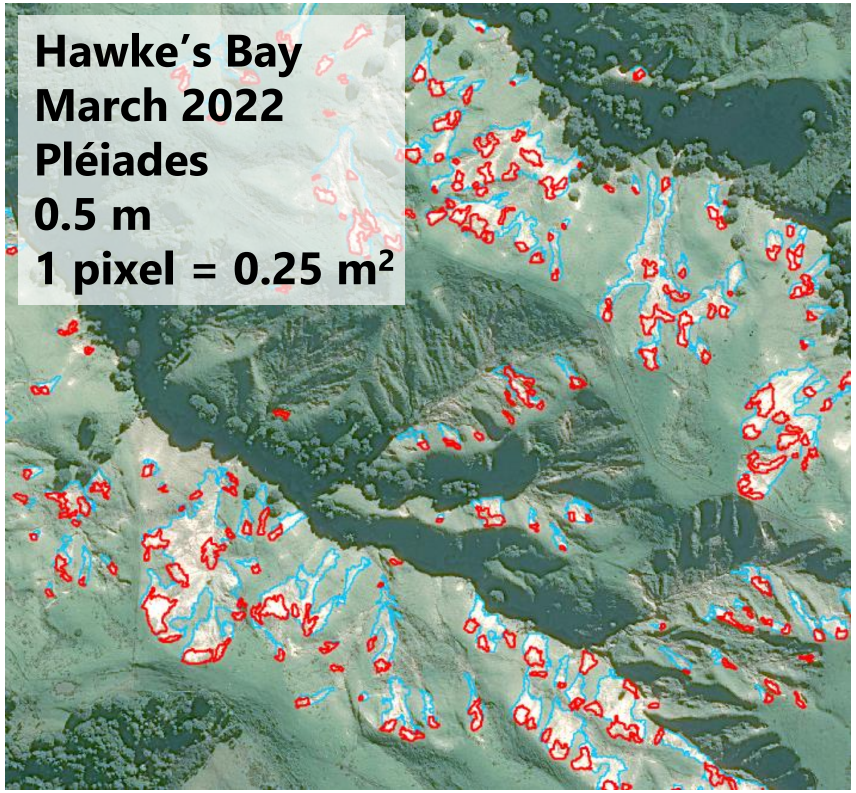
2.2 Where does the data come from?

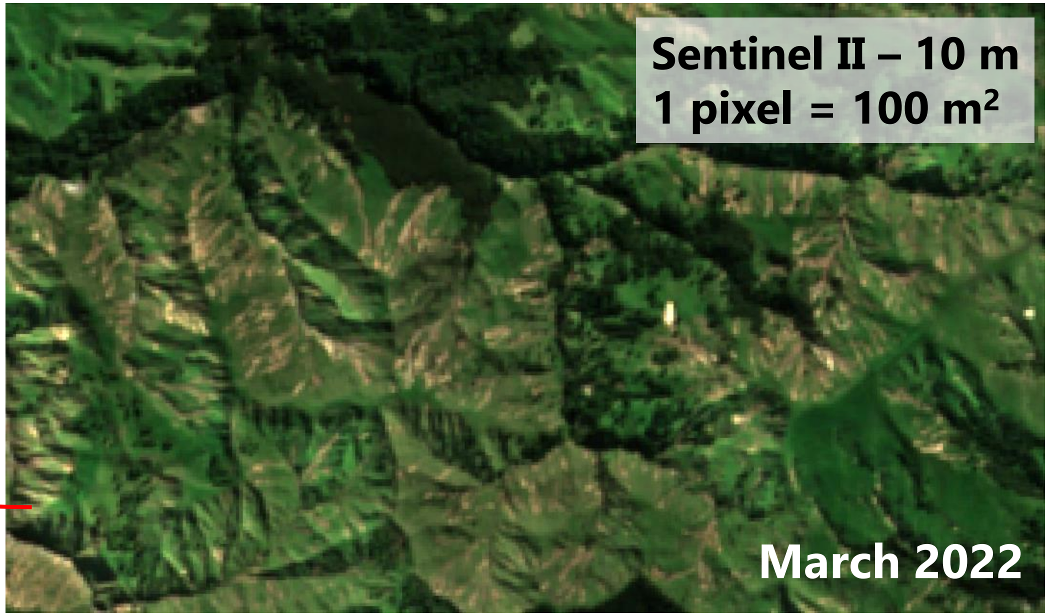
- Need repeated **high-resolution** imagery to differentiate landslide scars and deposits
- Used manual and automated mapping
- Assembled large inventory of shallow landslides

Median source area = 50 m²



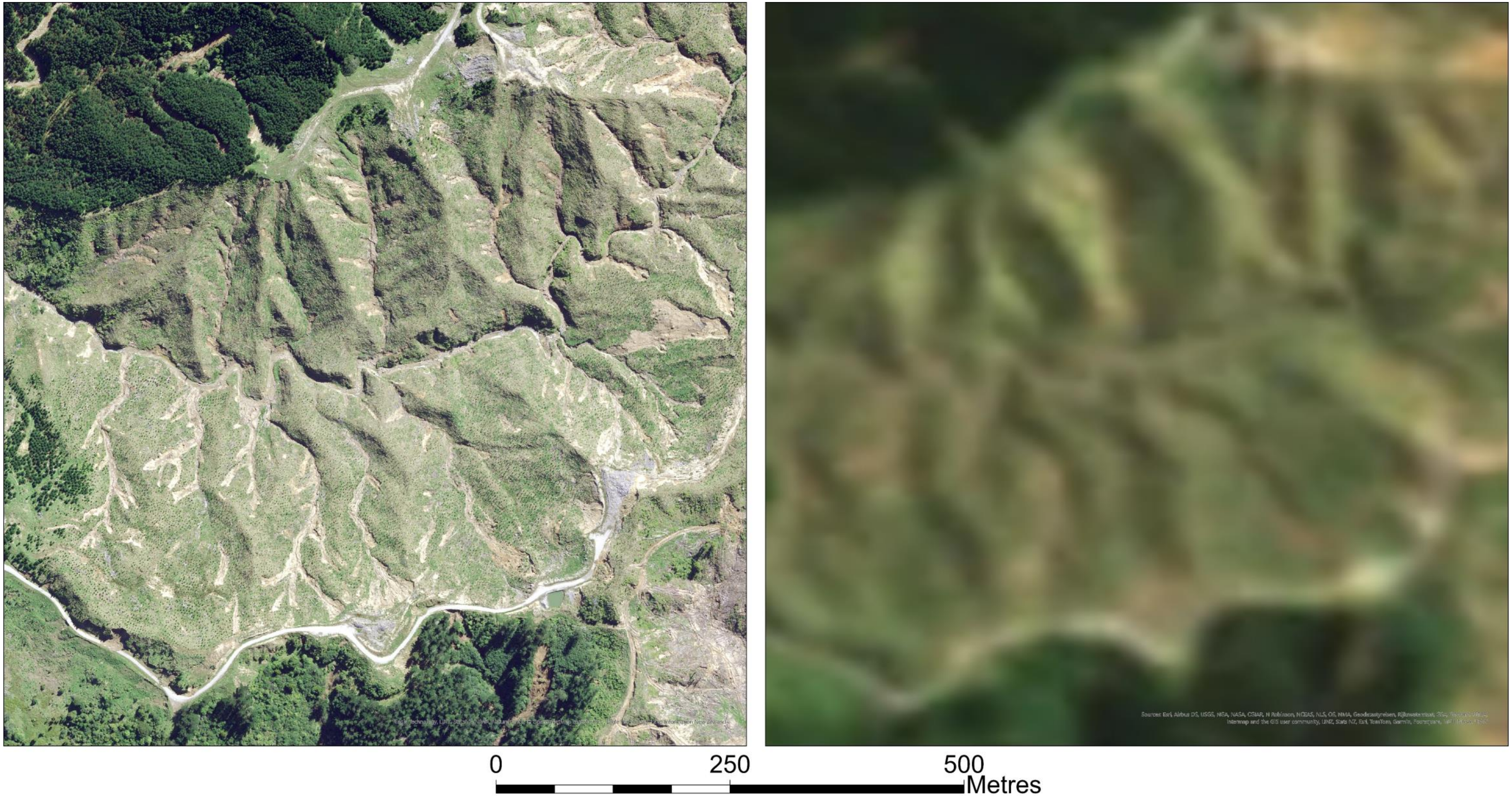
Typical source area distribution in soft-rock hill country





Imagery resolution comparison

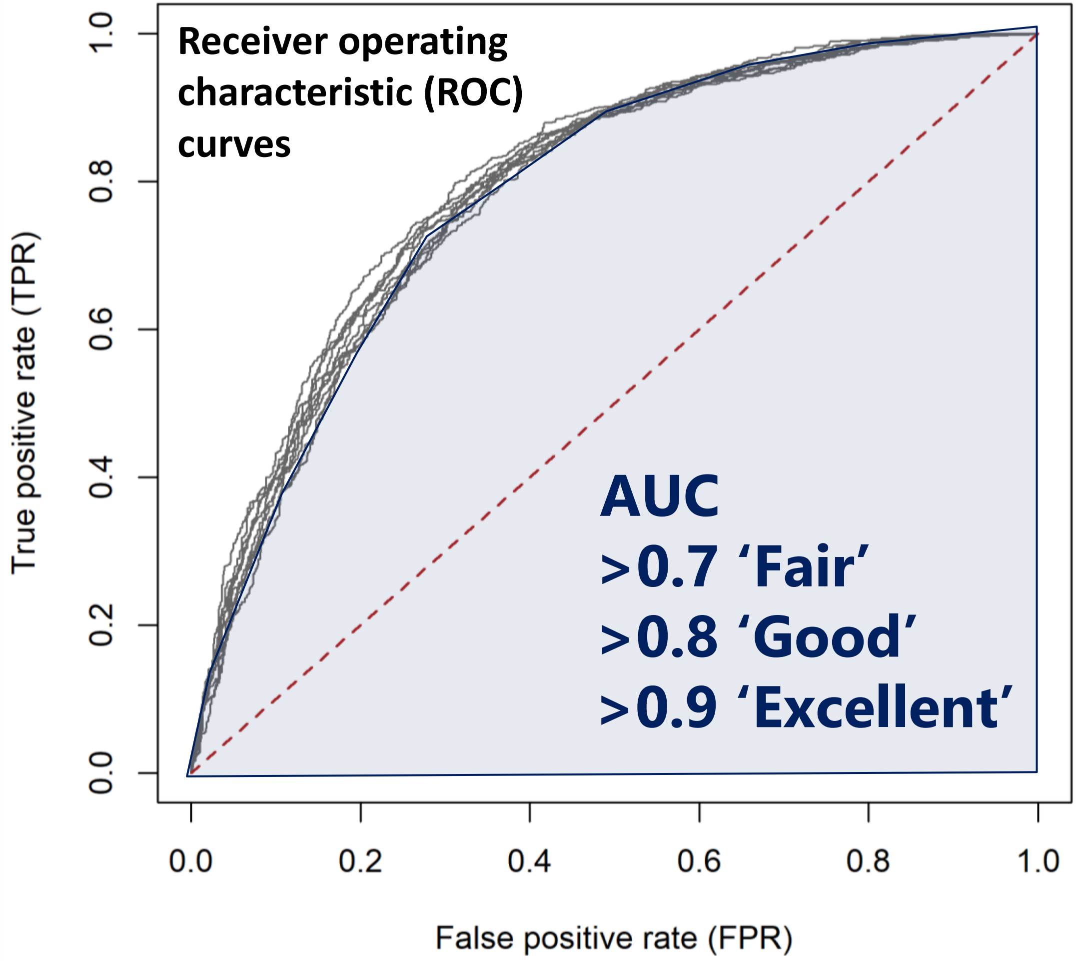
Aerial image (0.3 m) | **Sentinel 2 (10 m)**



2.3 Susceptibility modelling – logistic regression

Workflow

- ➢ Generate random non-landslide locations
- ➢ Extract co-variate data for landslide and non-landslide locations
- ➢ Train model to classify points
- ➢ Repeated cross-validation to evaluate predictive performance – **ROC AUC**
- ➢ Predict spatial probability (0 - 1) of future landslides



$$TPR = \frac{TP}{TP + FN} \qquad FPR = \frac{FP}{TN + FP}$$

2.4 Spatial prediction – Landslide susceptibility maps

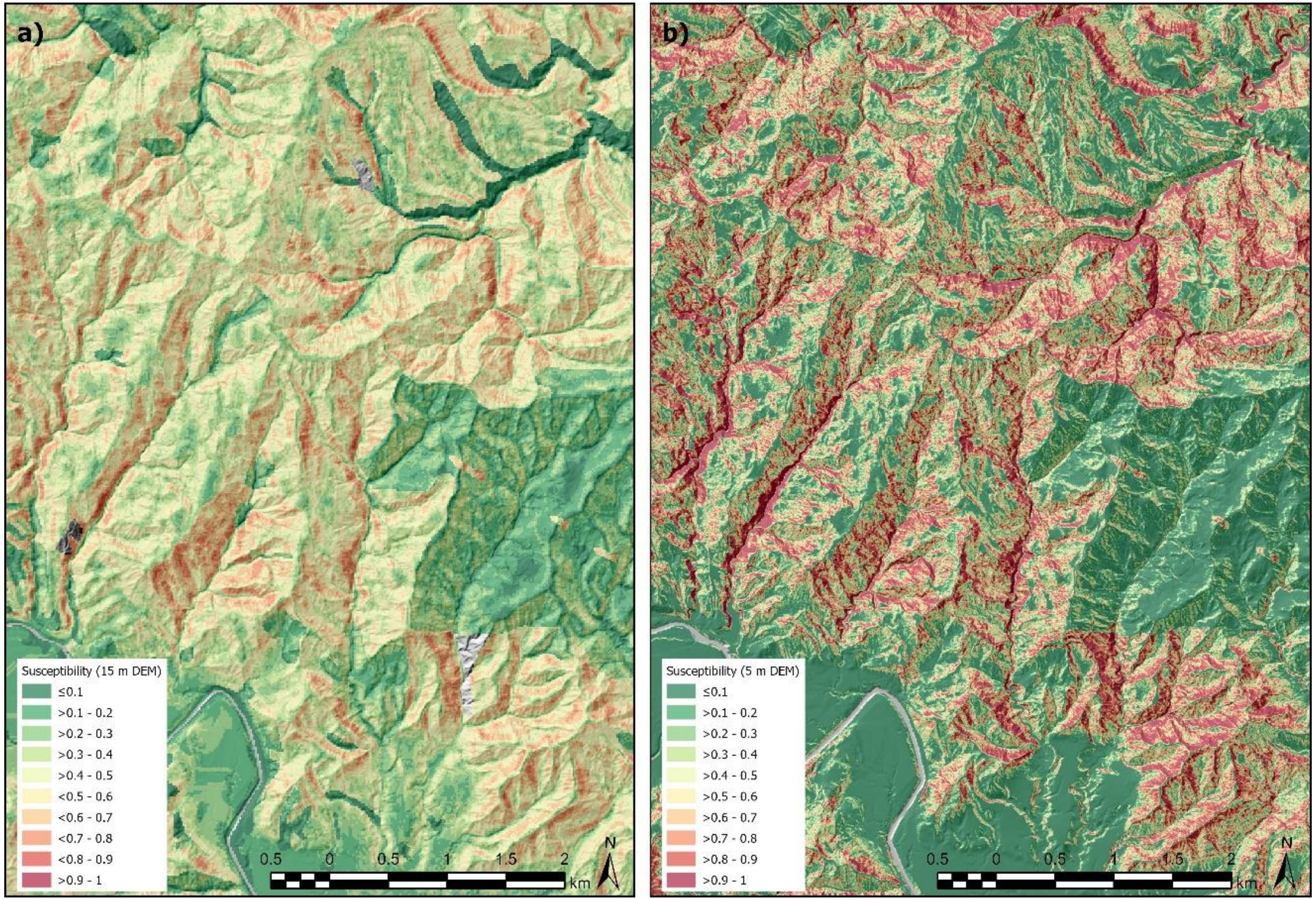
- Model used to produce susceptibility maps
- LiDAR DEM improved model accuracy from **72 to 88%** compared to national 15 m DEM in Wairarapa case study

CURRENT MODEL v1.0

- LiDAR-based (5 m DEM)
- 110,000 landslides from Hawke's Bay, Gisborne and Wairarapa
- Model performance:

AUC = 0.91 Accuracy = 84%

National 15 m DEM **LiDAR 5 m DEM**



2.5 Landslide-to-stream connectivity

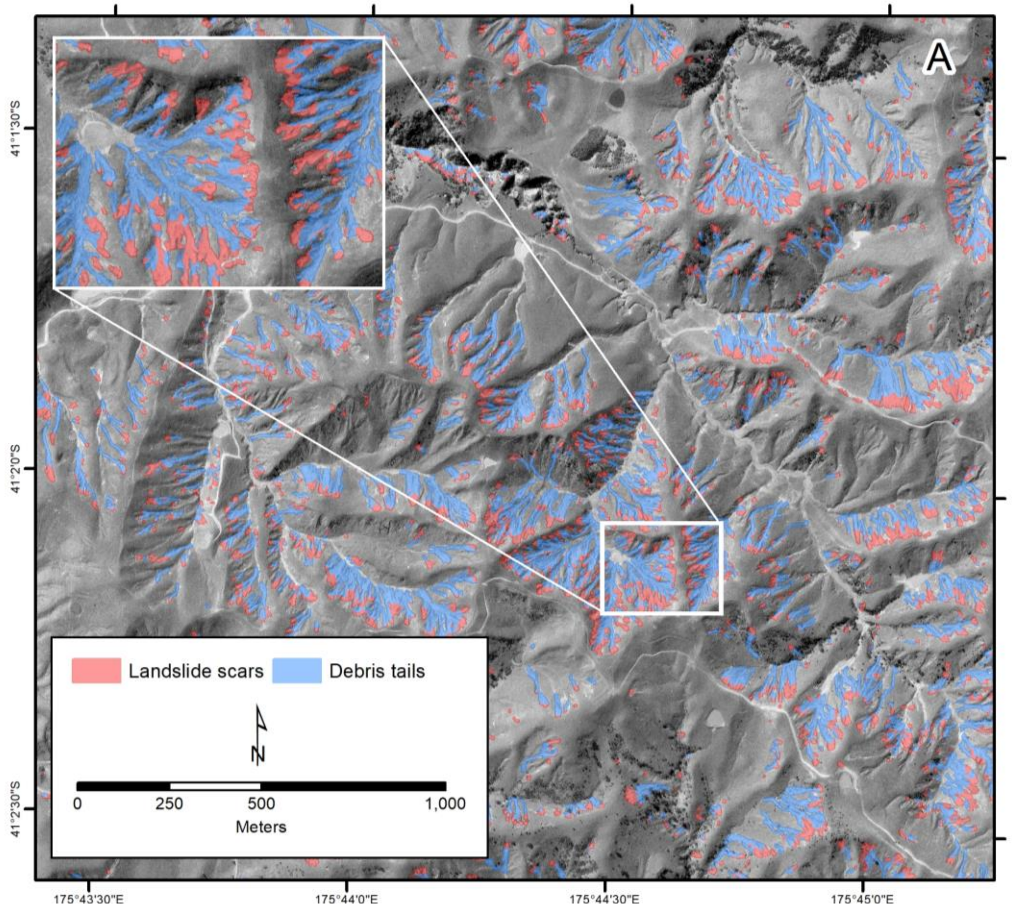
- **Connectivity:** intersection of landslide debris deposit and the digital channel network

INITIAL MODEL

- Developed first morphometric connectivity model (**AUC = 0.75**)
- Small sample size (*n* = 2,000 landslides)

UPDATED MODEL v1.0

- Improved connectivity model with expanded dataset (*n* = 41,000 landslides)
- Performance **AUC = 0.87**



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Ecological Engineering
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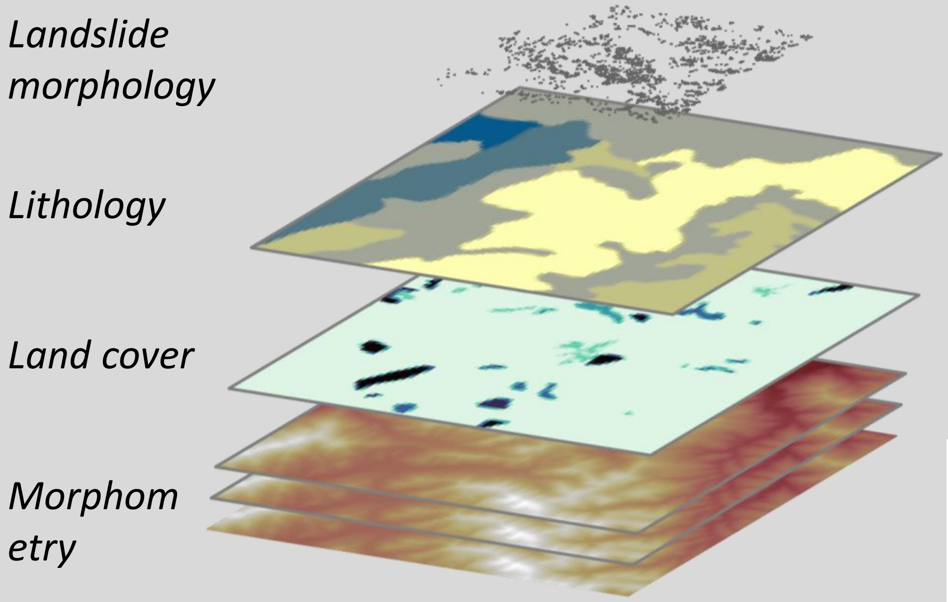
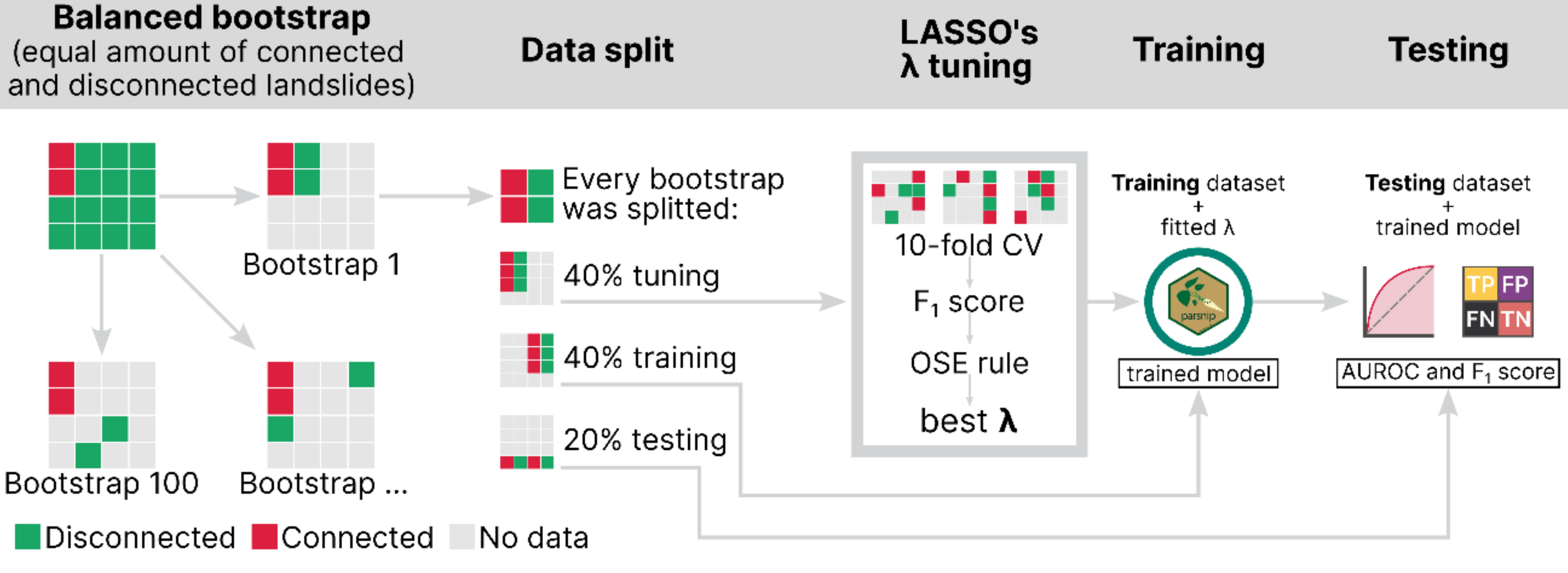
Development of a morphometric connectivity model to mitigate sediment derived from storm-driven shallow landslides

Raphael I. Spiekermann [a,b,*], Hugh G. Smith [a], Sam McColl [b], Lucy Burkitt [b], Ian C. Fuller [b]
[a] Manaaki Whenua – Landcare Research, Palmerston North, New Zealand
[b] School of Agriculture and Environment, Massey University, Palmerston North, New Zealand

2.5 Landslide connectivity – Modelling procedure (post-event)

Predictor variables:



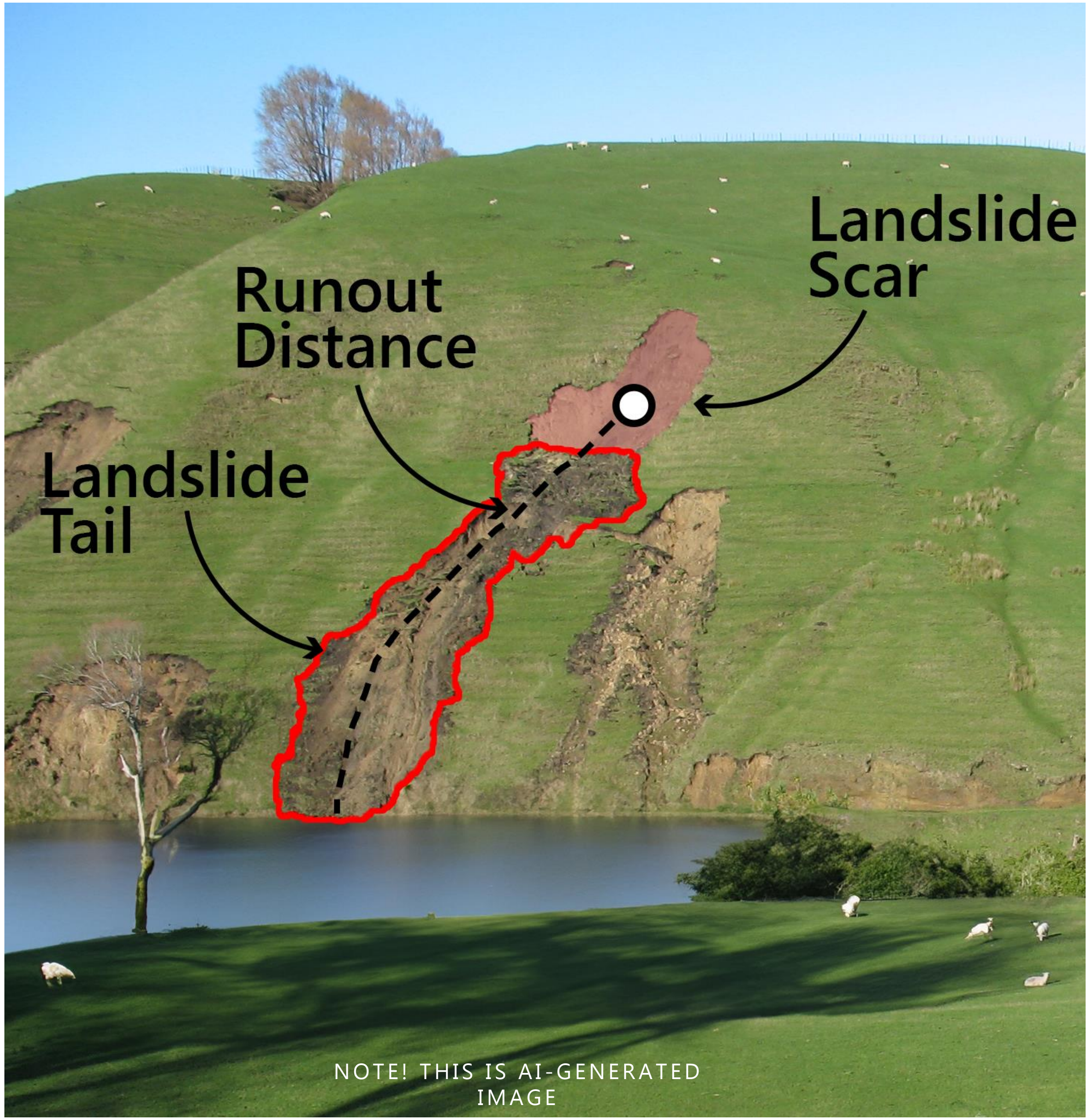


- **45 predictors** available for selection by the model
- Includes landslide scar area, number of coalescing scars, runout distance

- Automated variable selection – LASSO (least absolute shrinkage and selection operator)
- Only four predictors were selected by the model:
  - Downslope distance to the channel
  - **Landslide runout distance**
  - Maximum difference from mean elevation
  - Aspect

AUC score — **0.97** | Accuracy — **93%**

2.5 Connectivity – Multi-variable to single-variable model (pre-event)



Runout distance can only be measured **after the event**.
How can we predict **future** connectivity (i.e. pre-event)?

Single-variable logistic regression based on:

- **Downslope distance to the channel**

AUC score — **0.87** | Accuracy — **76%**

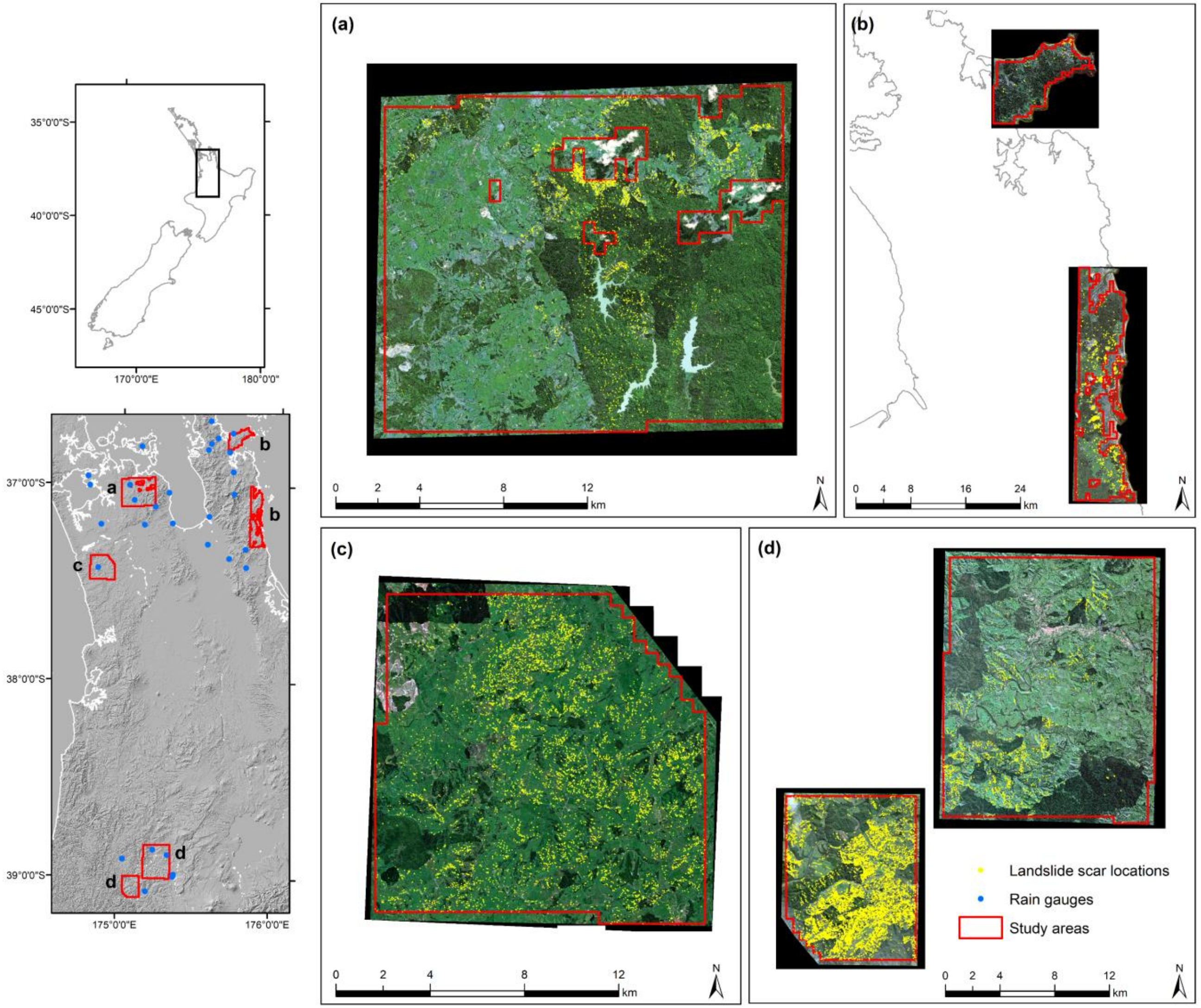
Downslope distance to the channel — distance from each grid cell in a raster to the nearest channel cell, measured along the downslope flowpath

3. Factors influence landslide occurrence – Findings from research

3.1 Which factors most influence the occurrence of shallow landslides?

- Focus on four storm events (2017-18)
- Study area selection:
  - ➢ cloud-free, before/after high-res satellite imagery (0.5 m)
  - ➢ weather radar coverage
  - ➢ variation in landslide density and rainfall

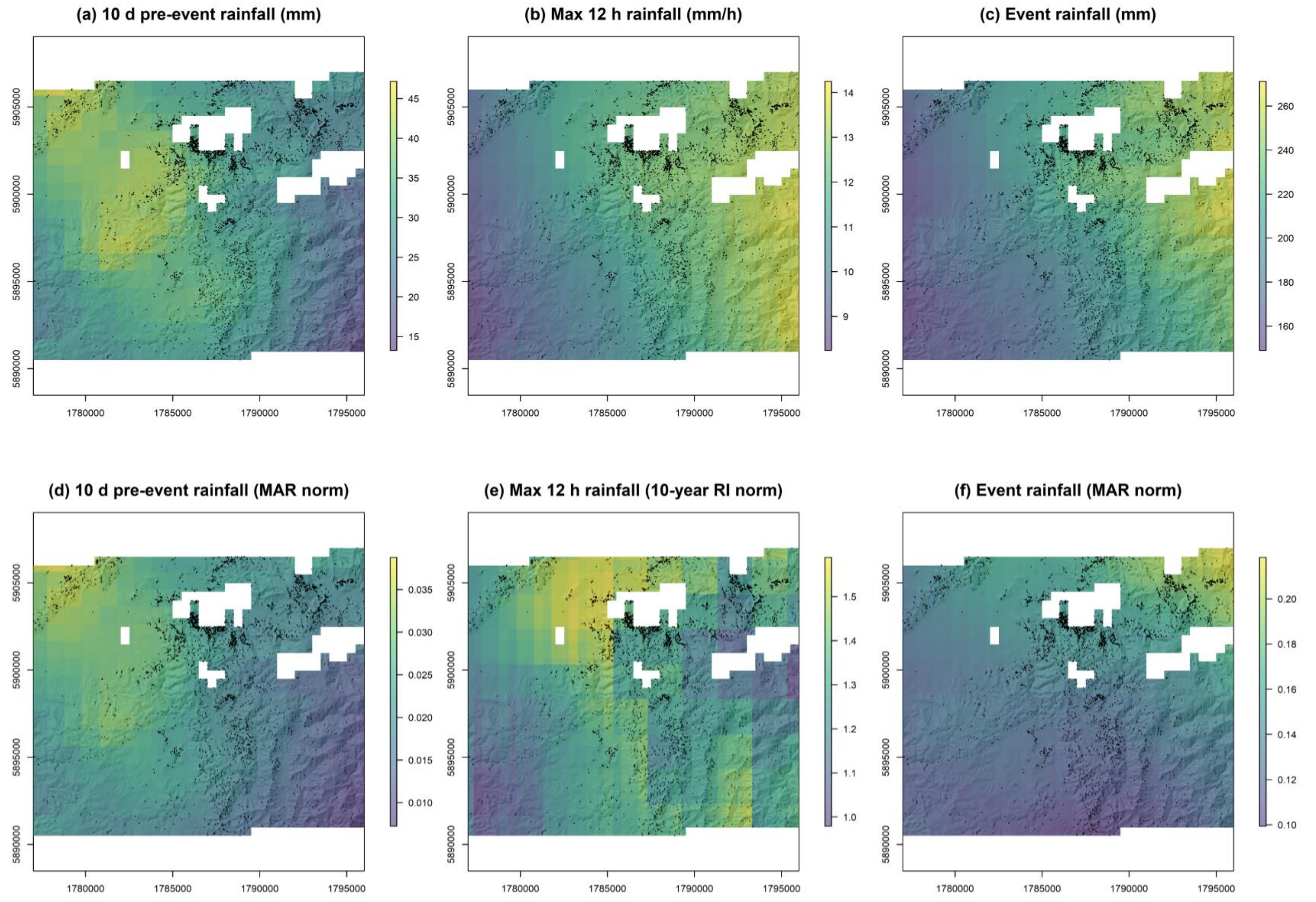
• Landslide *n*	26,500
• Total study area	1,117 km^2
• Max rainfall [ARI]	82-412 mm d^{-1} [<2 – 250 yrs]



3.2 Rainfall data – weather radar

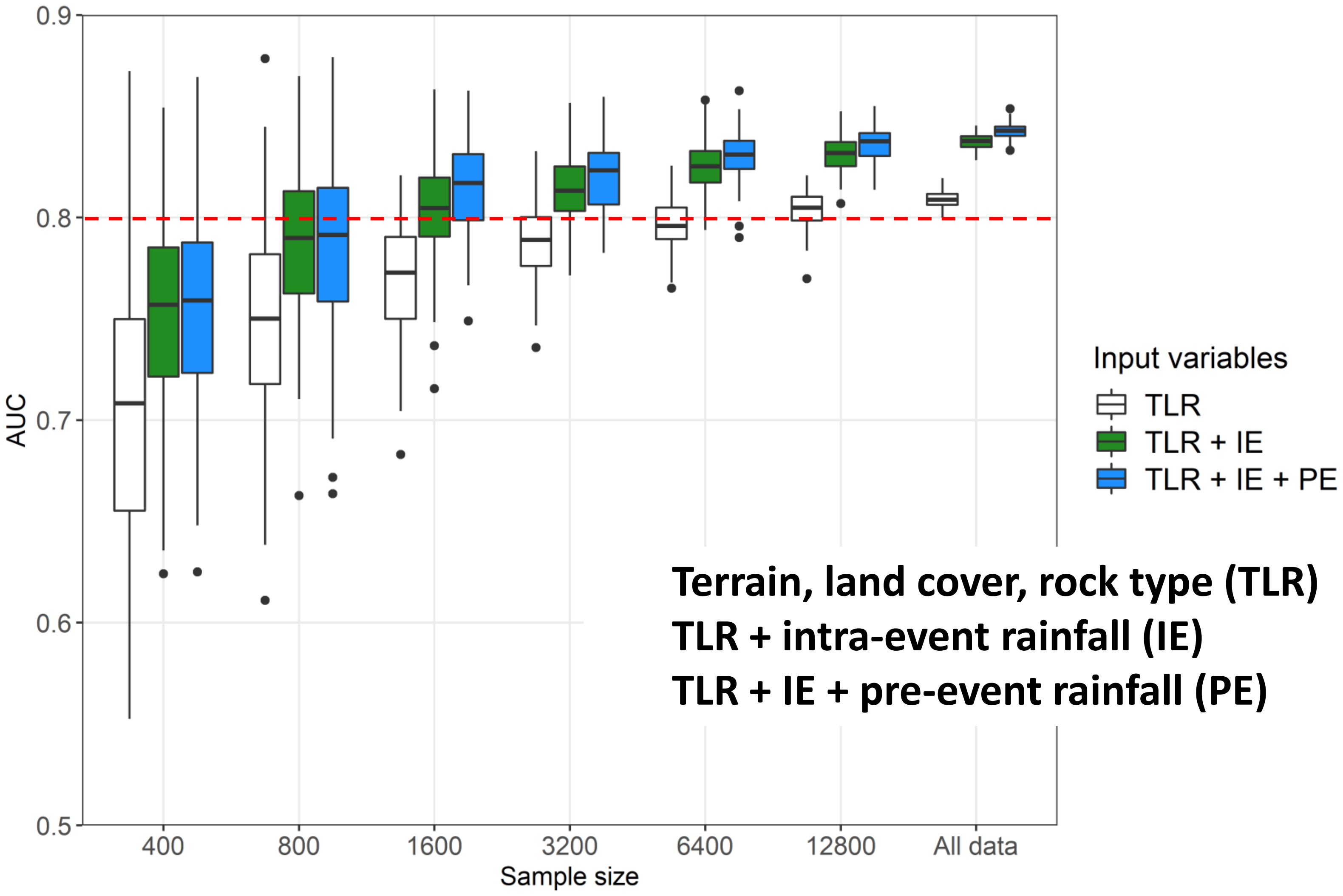
- Processed data on 1 km grid
- Rainfall metrics:
  - ➢ pre-event accumulations (10 – 90 d)
  - ➢ max intra-event intensities (30 min – 24 h)
  - ➢ total event rainfall

- Rainfall normalised by either:
  - ➢ Mean annual rainfall 1981 – 2010 (0.5 km)
  - ➢ 10-yr recurrence interval intensity, HIRDS v4 (2 km)



3.3 Statistical analysis & model performance

- Applied binary logistic regression with the group-based *least absolute shrinkage and selection operator* (LASSO)
- Repeated cross-validation to evaluate performance – ROC AUC
- Assessed sample size effect (*n* = 400 → all data)
- Not LiDAR based (unavailable)



Terrain, land cover, rock type (TLR)
TLR + intra-event rainfall (IE)
TLR + IE + pre-event rainfall (PE)

3.4 Factors influencing landslide occurrence

- Model coefficients expresses the relative influence of each factor on landslide occurrence

Increase susceptibility (+)		Decrease susceptibility (-)	
Pasture	1.08	Indigenous forest	0.95
Slope	0.79	Exotic forest	0.58
Harvested forest	0.65	Broadleaf indigenous hardwoods	0.22
Max 12 h intensity	0.62	Planar or flat land	0.19 0.14
10 d pre-event	0.62	Ashes older than Taupo pumice	0.12
Event rainfall	0.48	Alluvium & colluvium	0.11

	TLR	TLR + IE	TLR + IE + PE
10d accum norm	NA	NA	0.62
30d accum norm	NA	NA	NA
60d accum norm	NA	NA	0.02
90d accum norm	NA	NA	0.01
i30min norm	NA	NA	NA
i60min norm	NA	NA	0.16
i2h norm	NA	NA	0.04
i6h norm	NA	0.05	0.07
i12h norm	NA	0.43	0.62
i24h norm	NA	NA	-
Event rainfall norm	NA	0.47	0.48
Slope	0.76	0.68	0.79
Flow Accumulation	0	0.01	0
Concave	0.06	0.05	0.07
Convex	0.1	0.1	0.12
Profile flat	-0.17	-0.16	-0.19
Converge	0.18	0.14	0.18
Diverge	-0.06	-0.03	-0.04
Planform flat	-0.12	-0.11	-0.14
NW	0.04	0.01	0.01
N	0.05	0.03	0.03
NE	0.11	0.07	0.07
E	0.11	0.07	0.07
SE	0.02	0.01	0.01
S	-0.09	-0.05	-0.06
SW	-0.16	-0.09	-0.08
W	-0.08	-0.05	-0.05
Soft volcanic rocks - weathered	-0.02	-0.06	-0.01
Hard volcanic rocks (incl. lavas, ignimbrite)	0.08	-0.11	-0.01
Taupo & Kaharoa breccia & volcanic alluvium	-0.34	-0.19	-0.06
Sandstone - massive	0.28	0.45	0.21
Ashes older than Taupo pumice	-0.59	-0.41	-0.12
Mudstone - massive	0.47	0.33	0.19
Mudstone - jointed	0.06	0.31	0.06
Mudstone - banded	-0.13	-0.06	0
Greywacke - weathered	0.42	-0.01	-0.06
Greywacke	0.21	0.04	-0.02
Argillite	-0.28	-0.08	-0.07
Alluvium & colluvium	-0.17	-0.21	-0.11
Manuka/Kanuka	0.02	0.04	0.03
Pasture	0.77	1.08	1.08
Forest - harvested	1.13	0.67	0.65
Exotic forest	-0.58	-0.63	-0.58
Broadleaved indigenous hardwoods	-0.24	-0.17	-0.22
Indigenous forest	-1.11	-1.01	-0.95

3.5 How does landslide density vary with rainfall and land cover?

For soft sedimentary rocks:

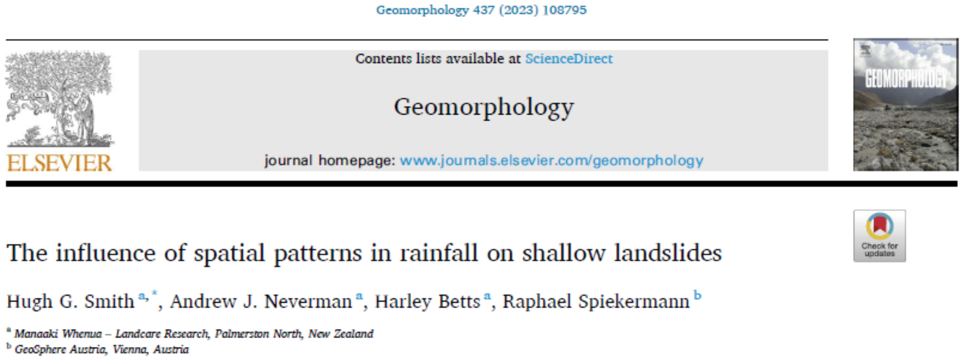
- **15-fold** increase in landslide density for pasture vs. forest
- Densities in forests range 0.5 – 27 scars km^{-2}
- Step change in densities on **pasture**:

  - **Max 12-hr intensity exceeds 10-yr ARI by ≥ 25%**

    50 – 72 vs. 234 scars km^{-2} (**> 3-fold ↑**)

  - **Event total ≥ 10% of mean annual rainfall**

    17 – 87 vs. 181 scars km^{-2} (**> 2-fold ↑**)


Geomorphology 437 (2023) 108795

Contents lists available at ScienceDirect

Geomorphology

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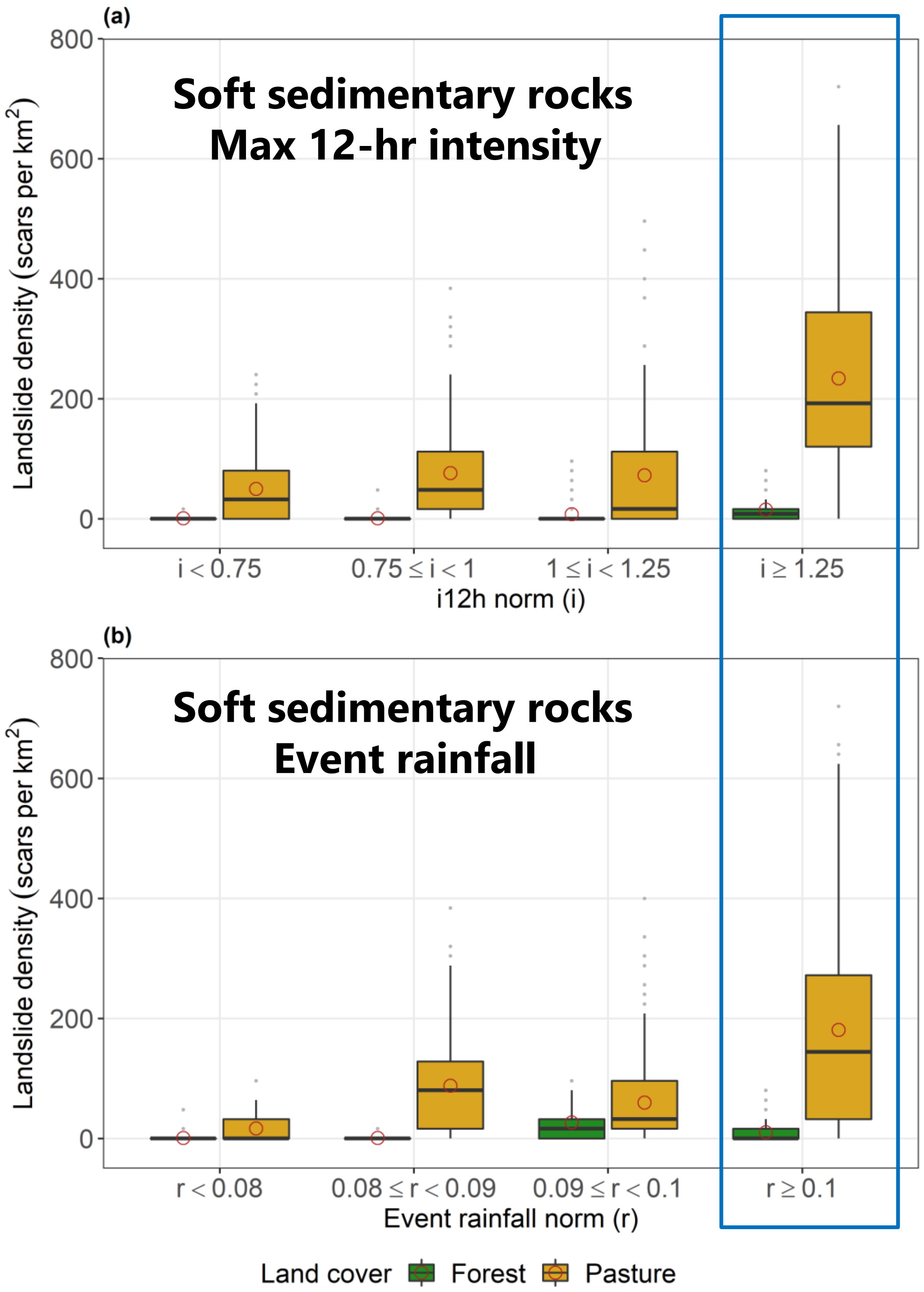
ELSEVIER

The influence of spatial patterns in rainfall on shallow landslides

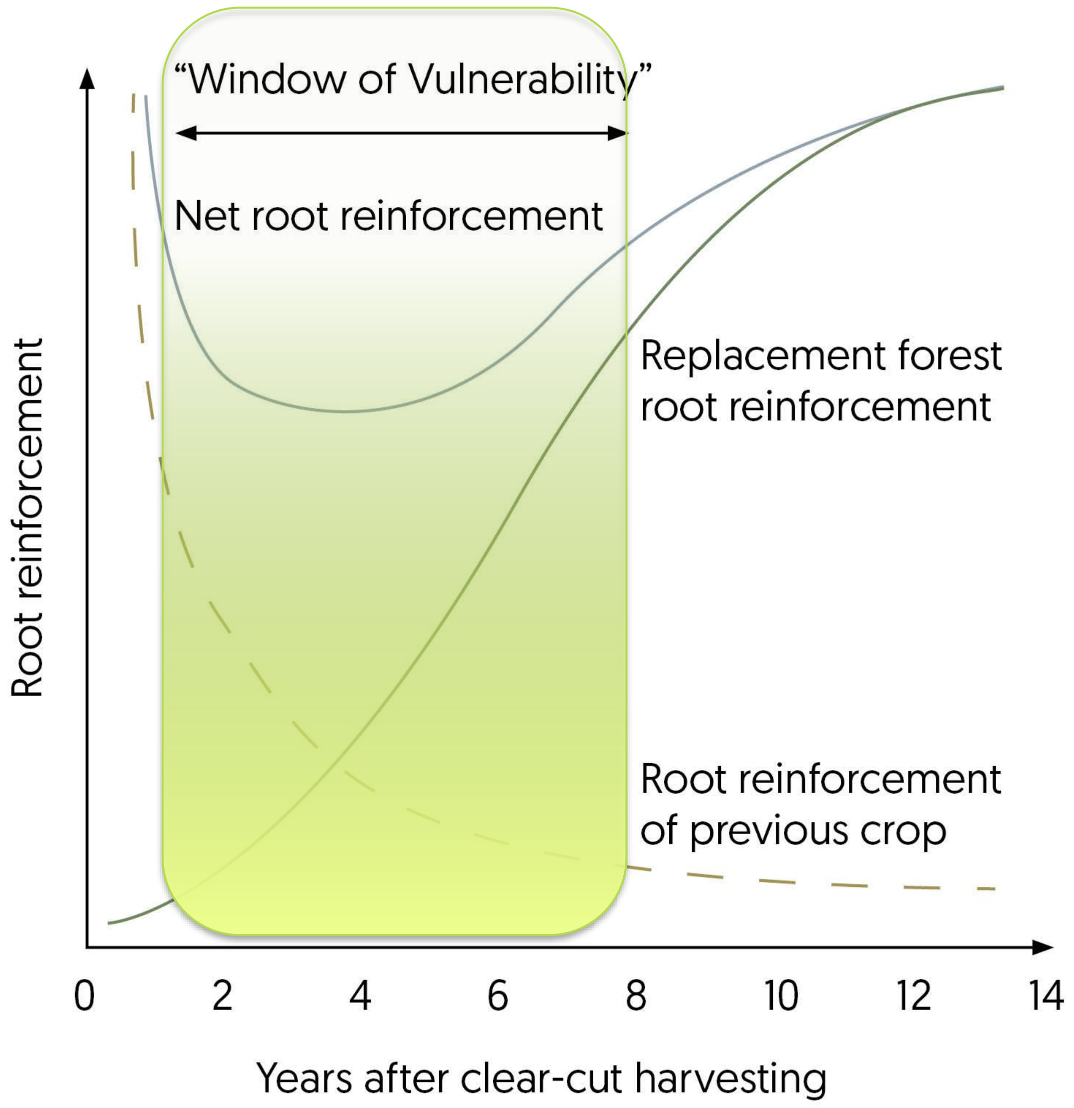
Hugh G. Smith[a,*], Andrew J. Neverman[a], Harley Betts[a], Raphael Spiekermann[b]

[a] Manaaki Whenua – Landcare Research, Palmerston North, New Zealand
[b] GeoSphere Austria, Vienna, Austria



3.6 What about the post-harvest 'window of vulnerability'?

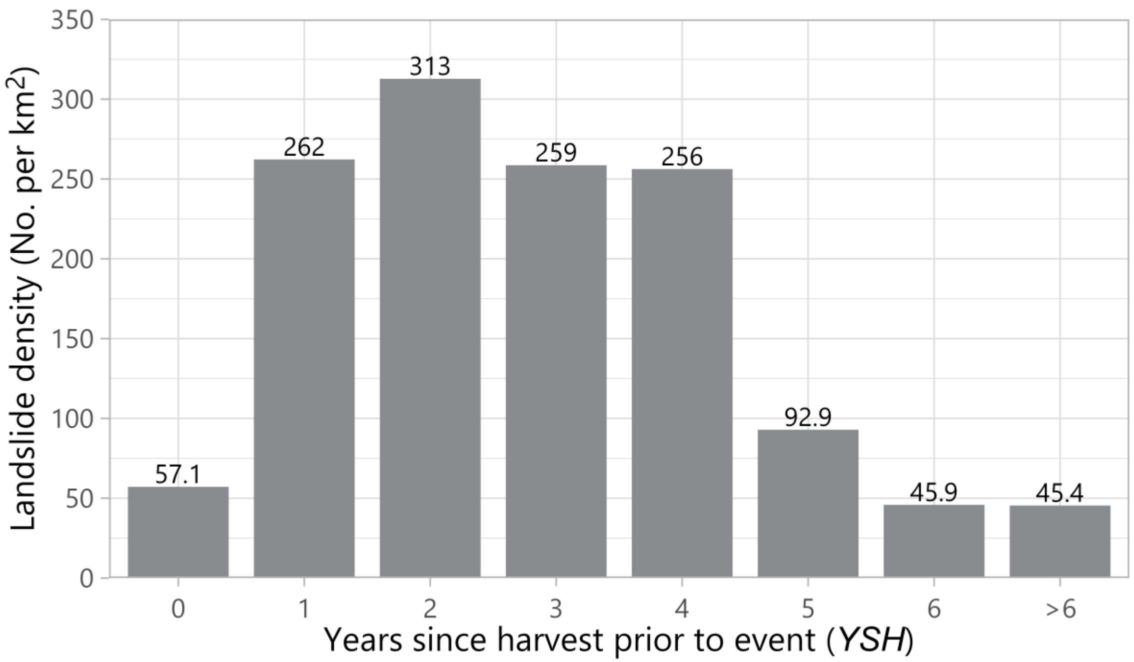
- Post-harvest 'window of vulnerability' has been widely recognised
- In the 'window of vulnerability' is there a time when landslide susceptibility is greatest?
- Study areas:
  - Tasman
  - Marlborough
  - Tolaga Bay

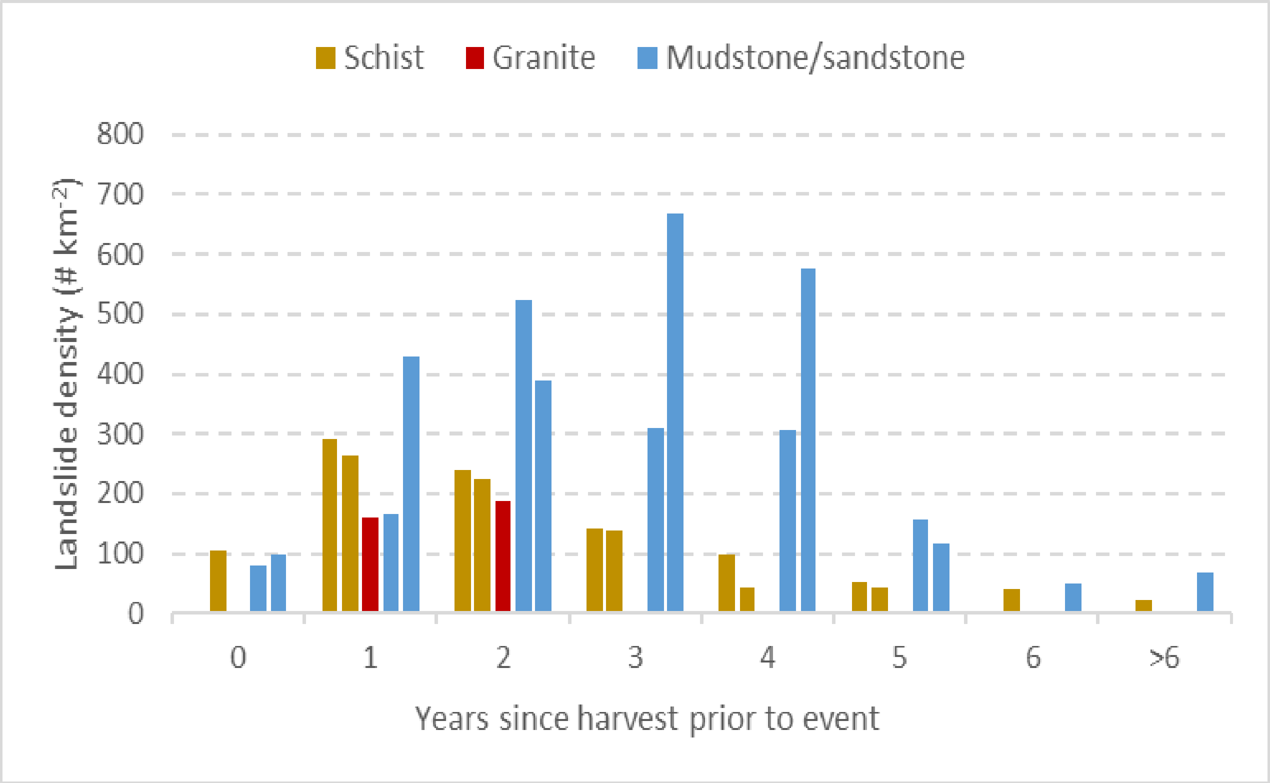


Δ roots + Δ hydrology = WoV (increased susceptibility)

3.6 What about the post-harvest ‘window of vulnerability’?

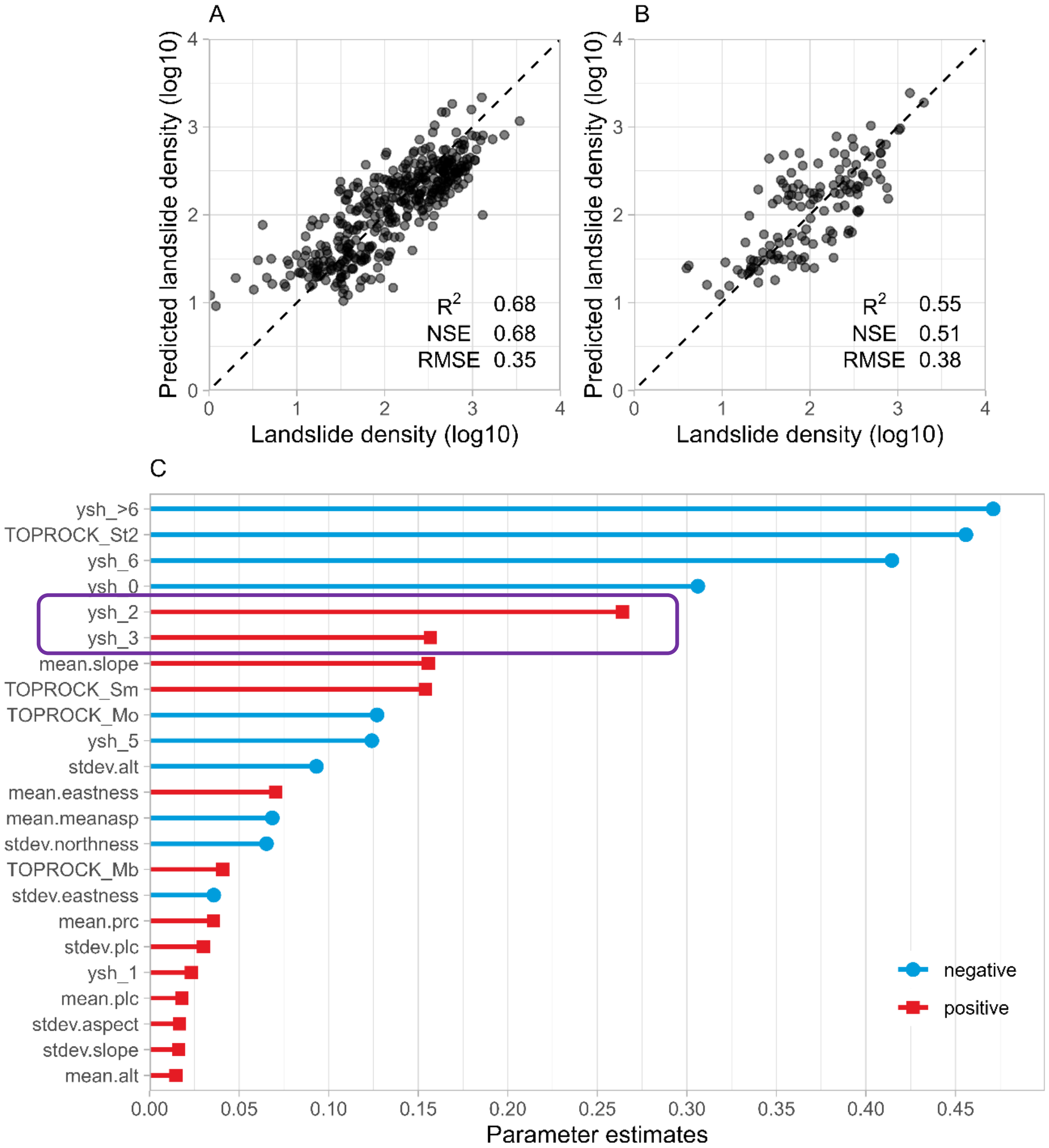
All sites combined





3.6 What about the post-harvest 'window of vulnerability'?

- Statistical model accounted for 55% of the variability in landslide density for Tolaga Bay and Marlborough (Tasman excluded)
- YSH one of most influential variables
- YSH 2 and YSH 3 positive influence along with slope and soft rock geology on density
- Most landslides not related to infrastructure



Ecological Engineering 206 (2024) 107300

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

ELSEVIER

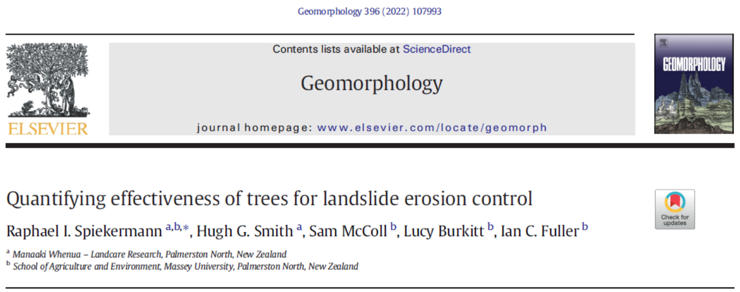
Exploring the post-harvest 'window of vulnerability' to landslides in New Zealand steepland plantation forests

Chris Phillips[a,*], Harley Betts[b], Hugh G. Smith[b], Anatolii Tsyplenkov[b]

[a] Manaaki Whenua – Landcare Research, PO Box 69040, Lincoln 7640, New Zealand
[b] Manaaki Whenua – Landcare Research, Private Bag 11052 Manawatu Mail Centre, Palmerston North 4442, New Zealand

3.7 How do spaced trees in pastoral areas influence landslide susceptibility?

- LiDAR used to map trees in pastoral areas
- 840 km^2 Wairarapa test area – mapped shallow landslides
- Modelled influence of individual trees on susceptibility
  - ➢ Tree Influence Model on Slope Stability (TIMSS)
- Recently updated TIMSS with new data from Hawke's Bay


Geomorphology 396 (2022) 107993

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Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Quantifying effectiveness of trees for landslide erosion control

Raphael I. Spiekermann [a,b,*], Hugh G. Smith [a], Sam McColl [b], Lucy Burkitt [b], Ian C. Fuller [b]

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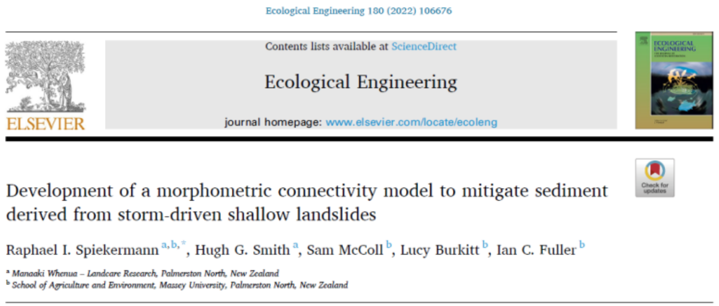
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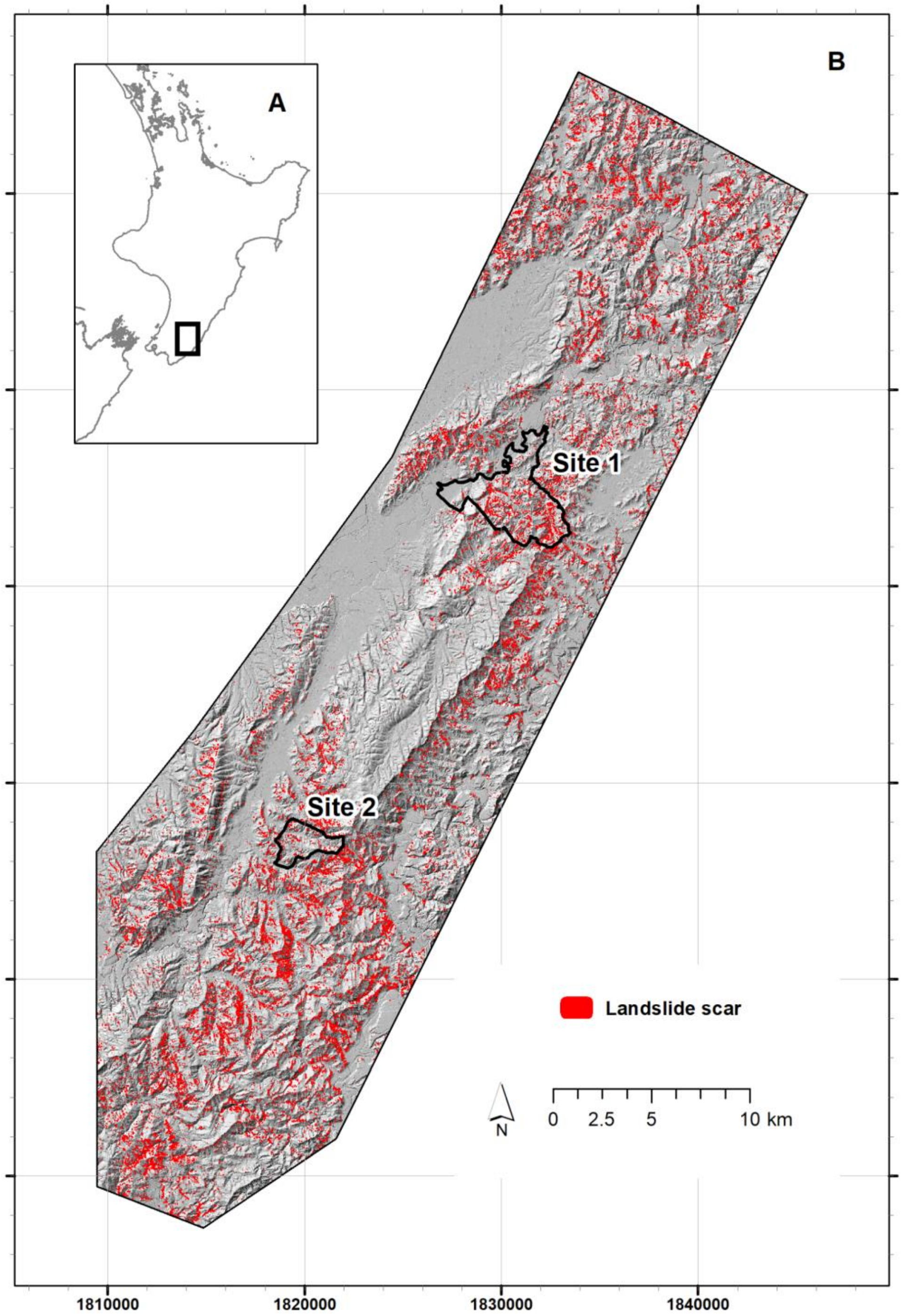
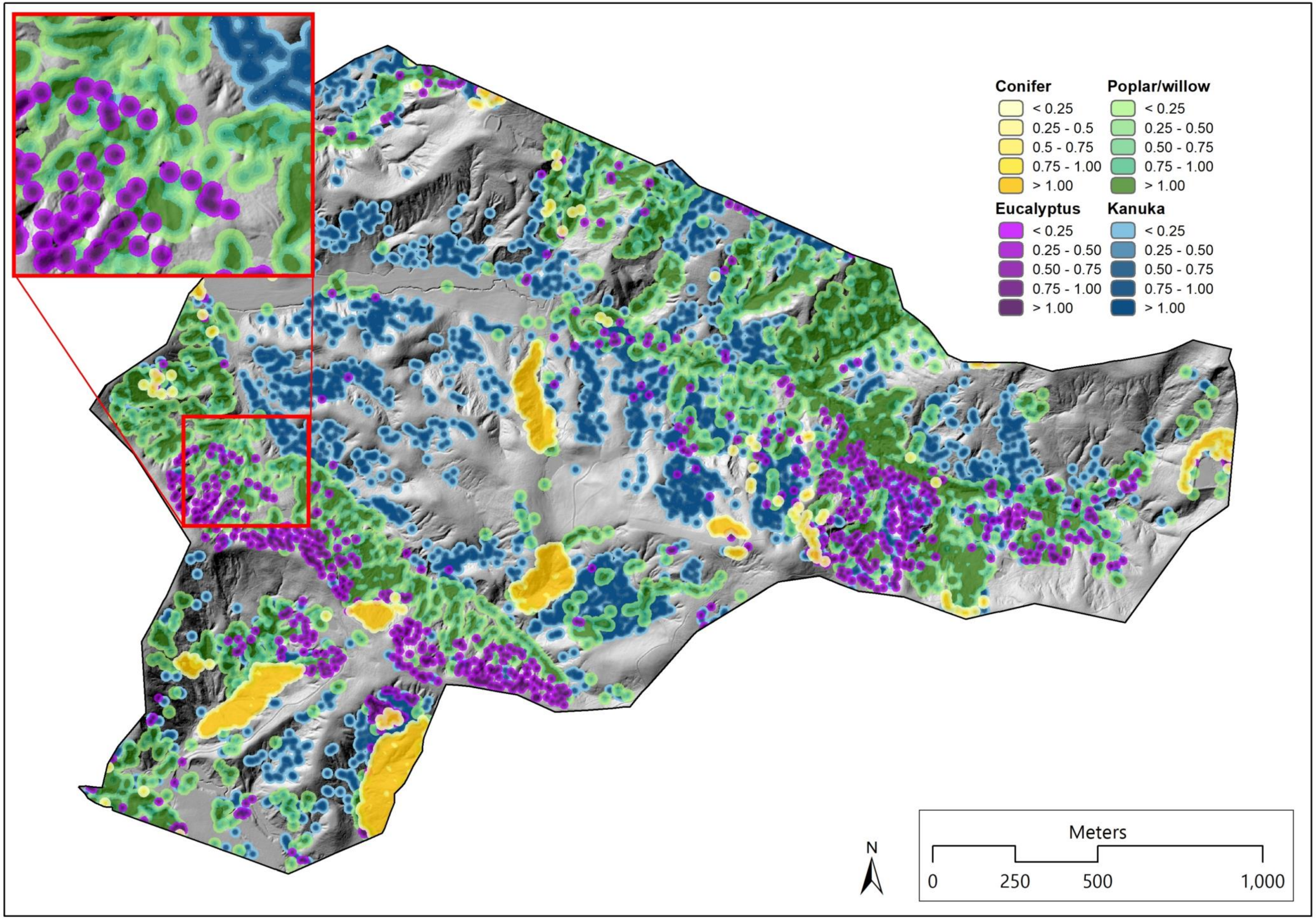
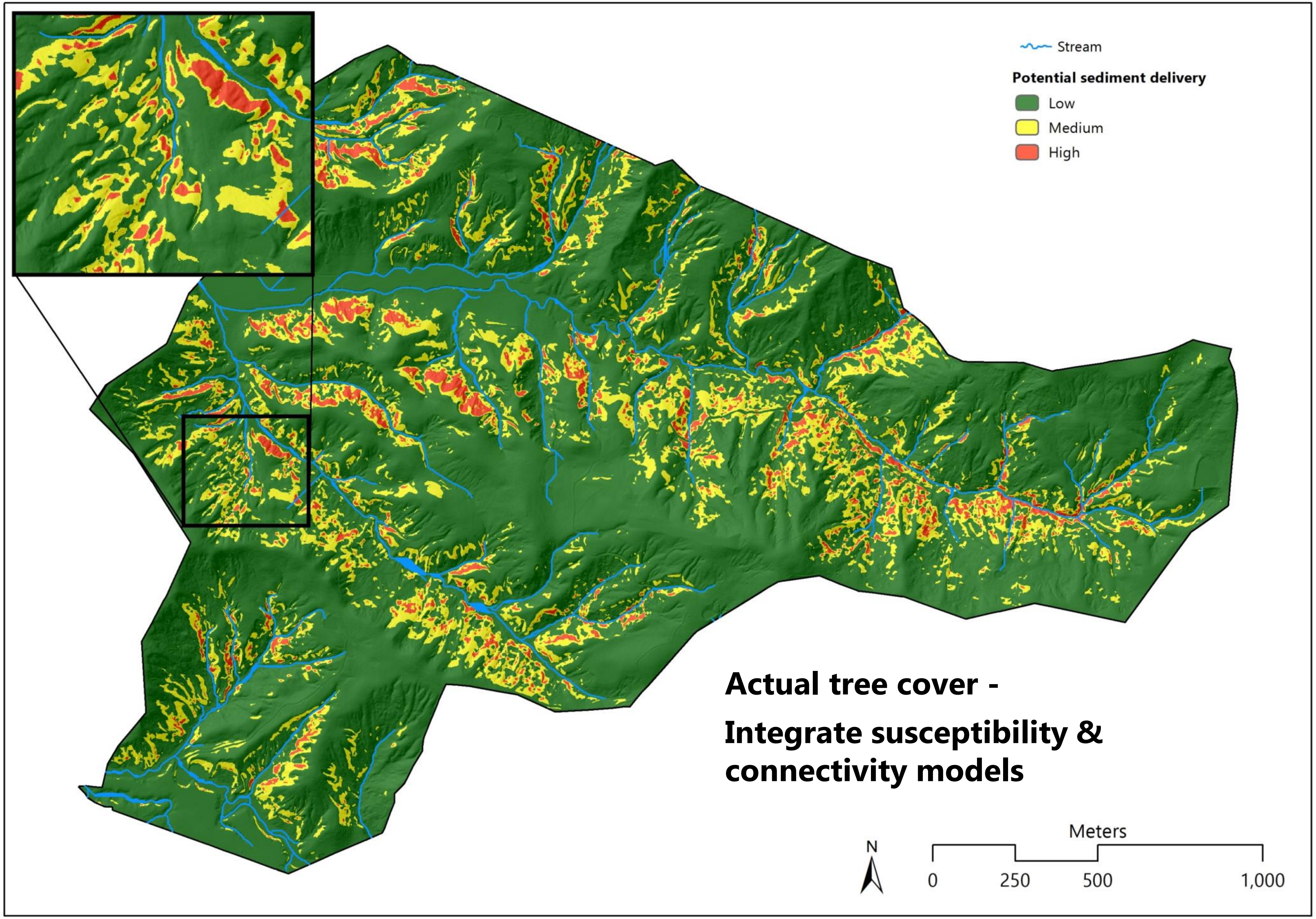


3.7 Tree influence in pastoral areas

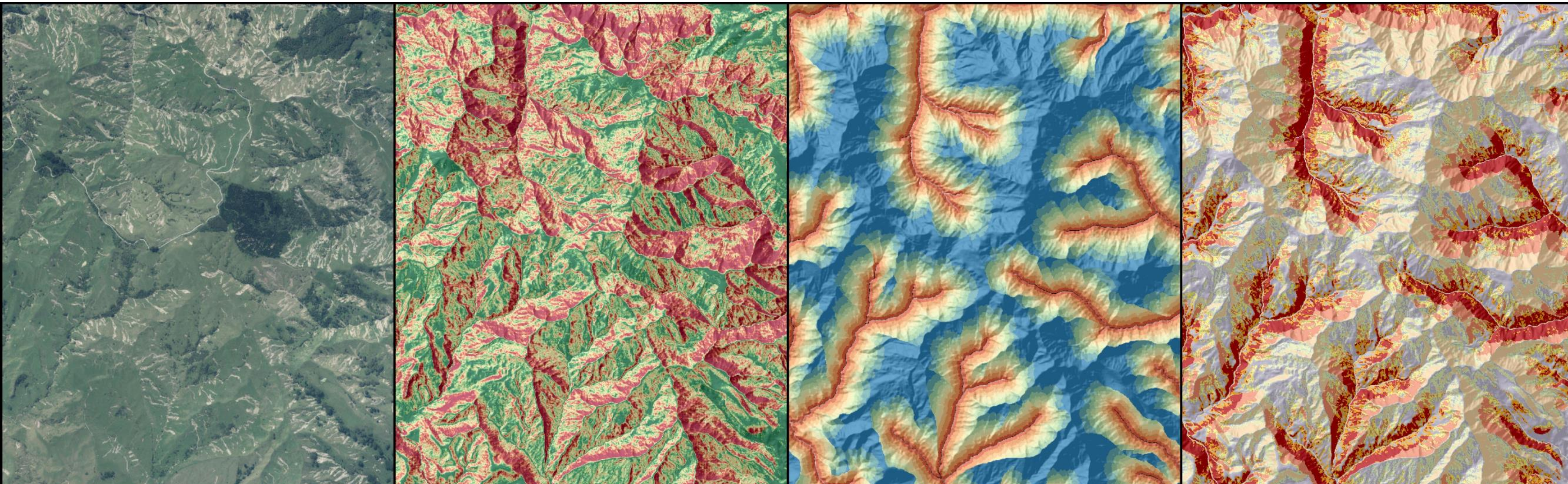
Tree influence model on slope stability (TIMSS)



3.7 Tree influence in pastoral areas



4. Tairāwhiti region shallow landslide susceptibility and connectivity layers



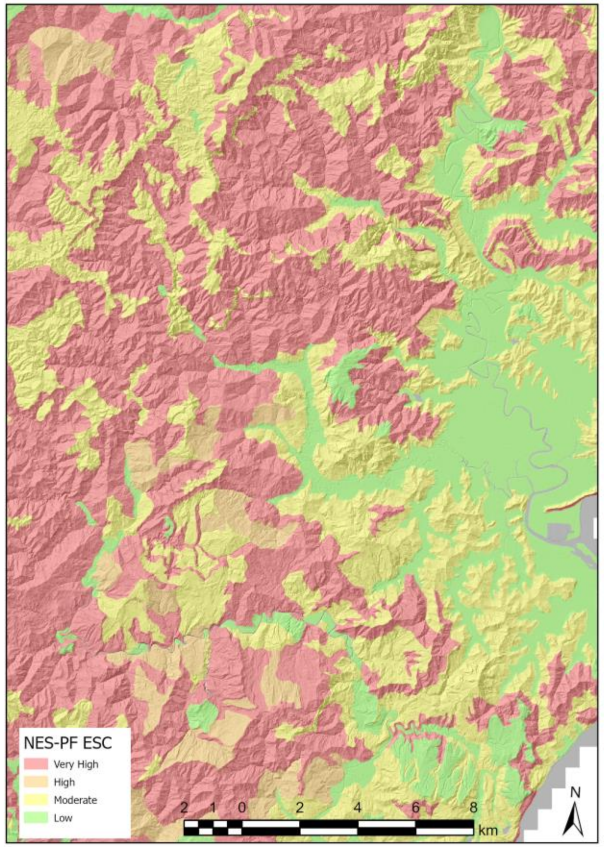
4.1 LiDAR-based shallow landslide susceptibility

- Maps produced and shared from August 2023
- Modelled forestry land with grass cover to express inherent susceptibility
- ESC assumes permanent grass cover (MPI, 2017)

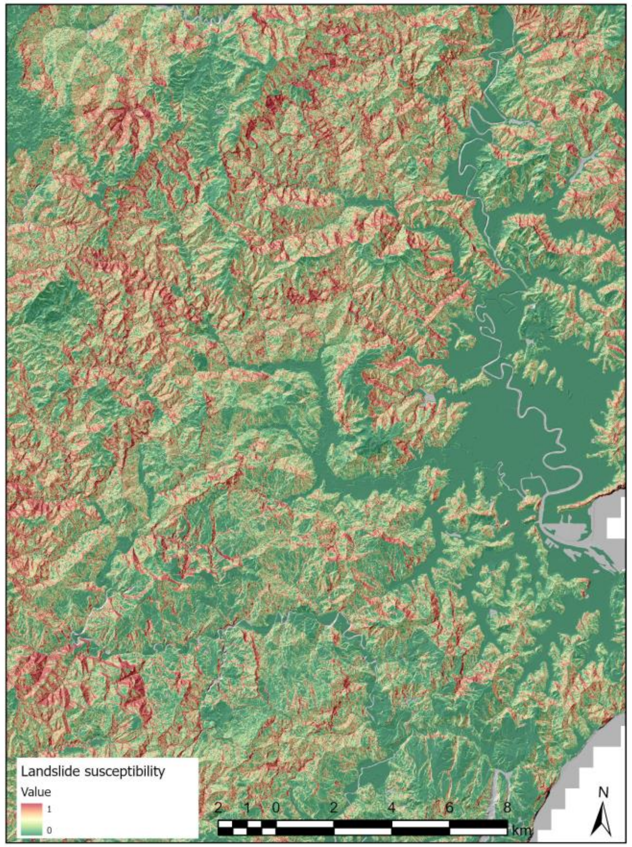
Gisborne – 'Forestry to grass' landslide susceptibility layer (5 m)

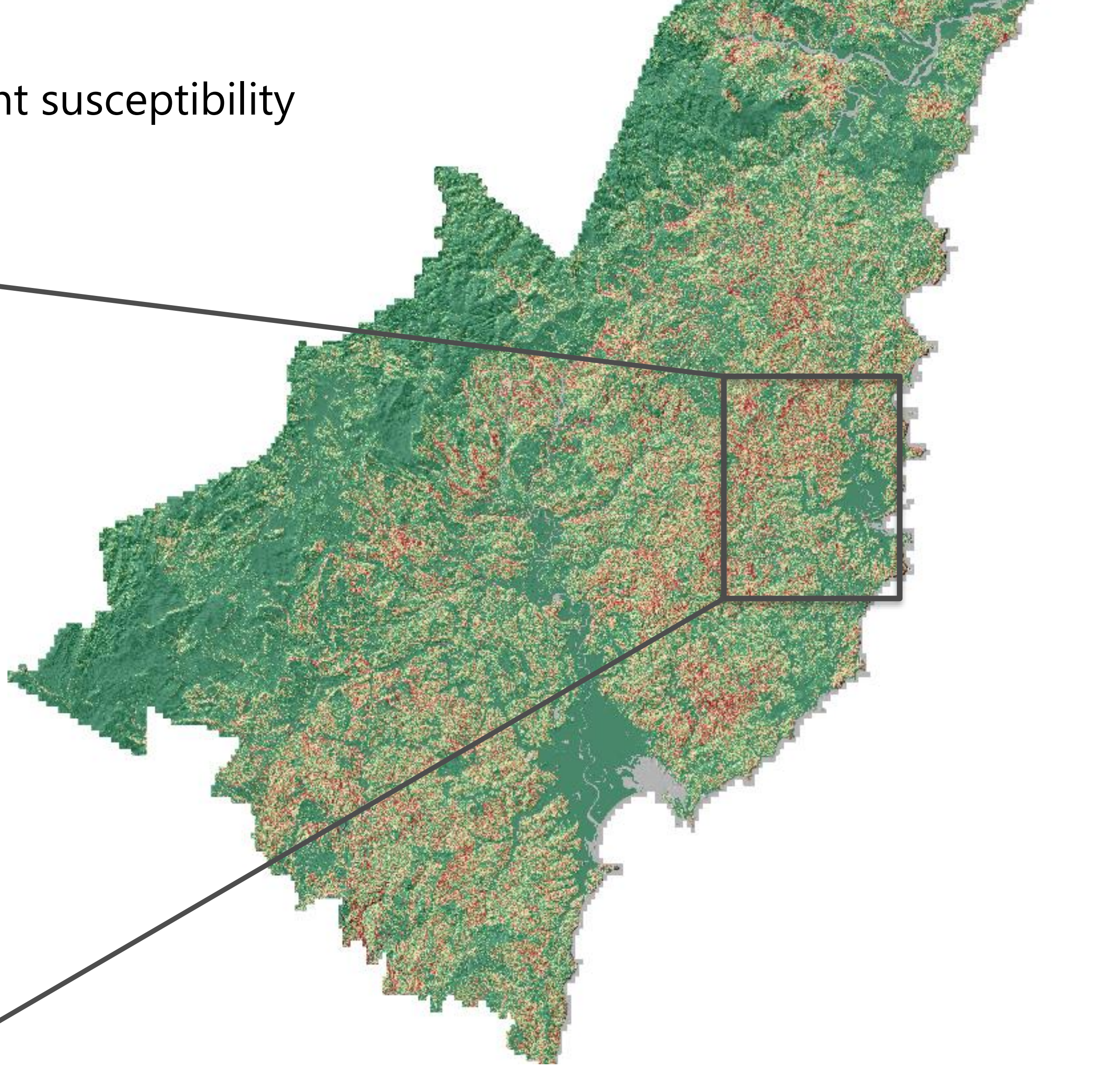
Areas mapped in LCDB v5 (2018) as 'Exotic Forest' or 'Forest – Harvested' converted to grass cover for analysis

ESC NES-CF



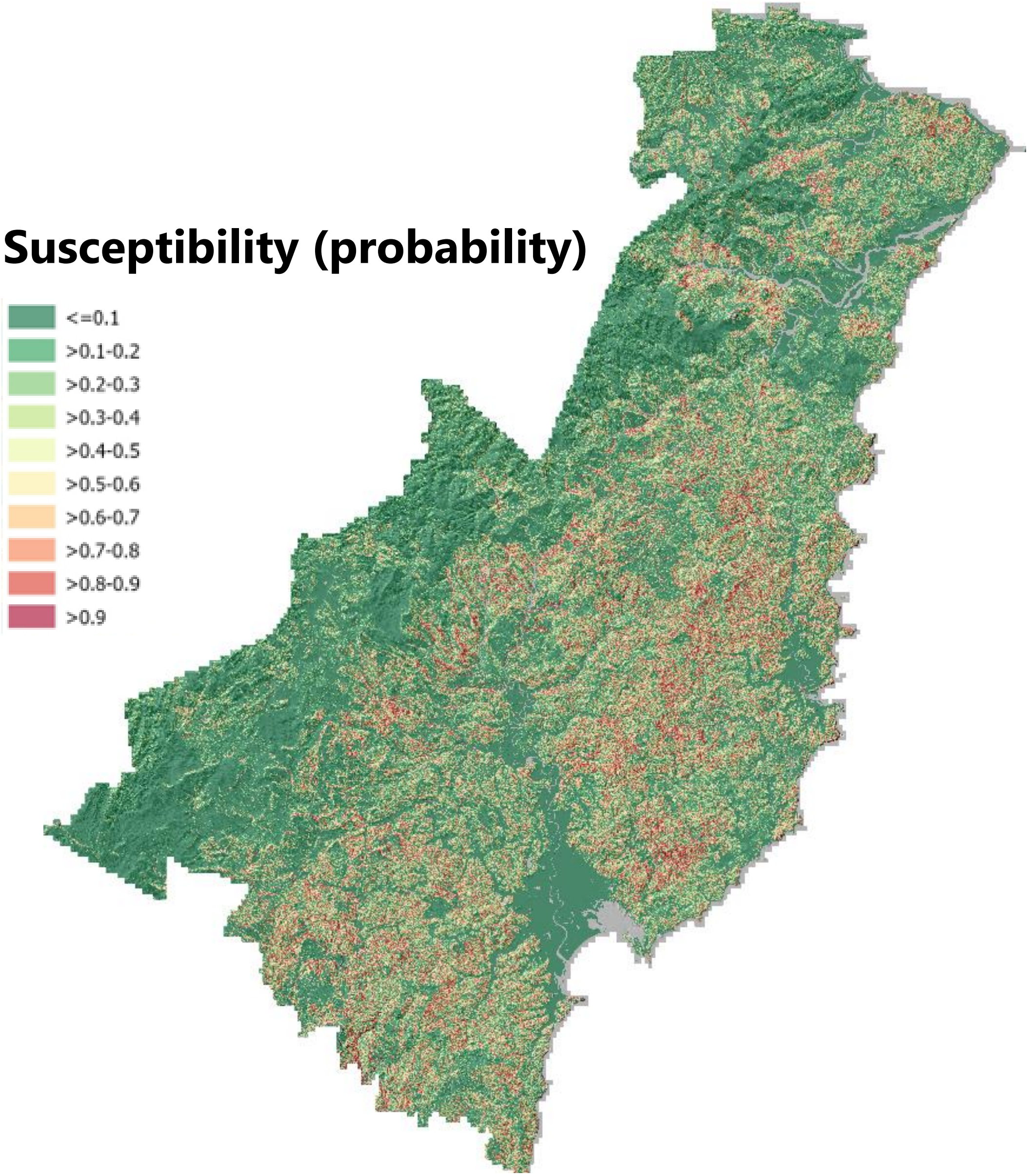
LiDAR-based





4.1 Landslide susceptibility – from probability to class

Susceptibility (probability)

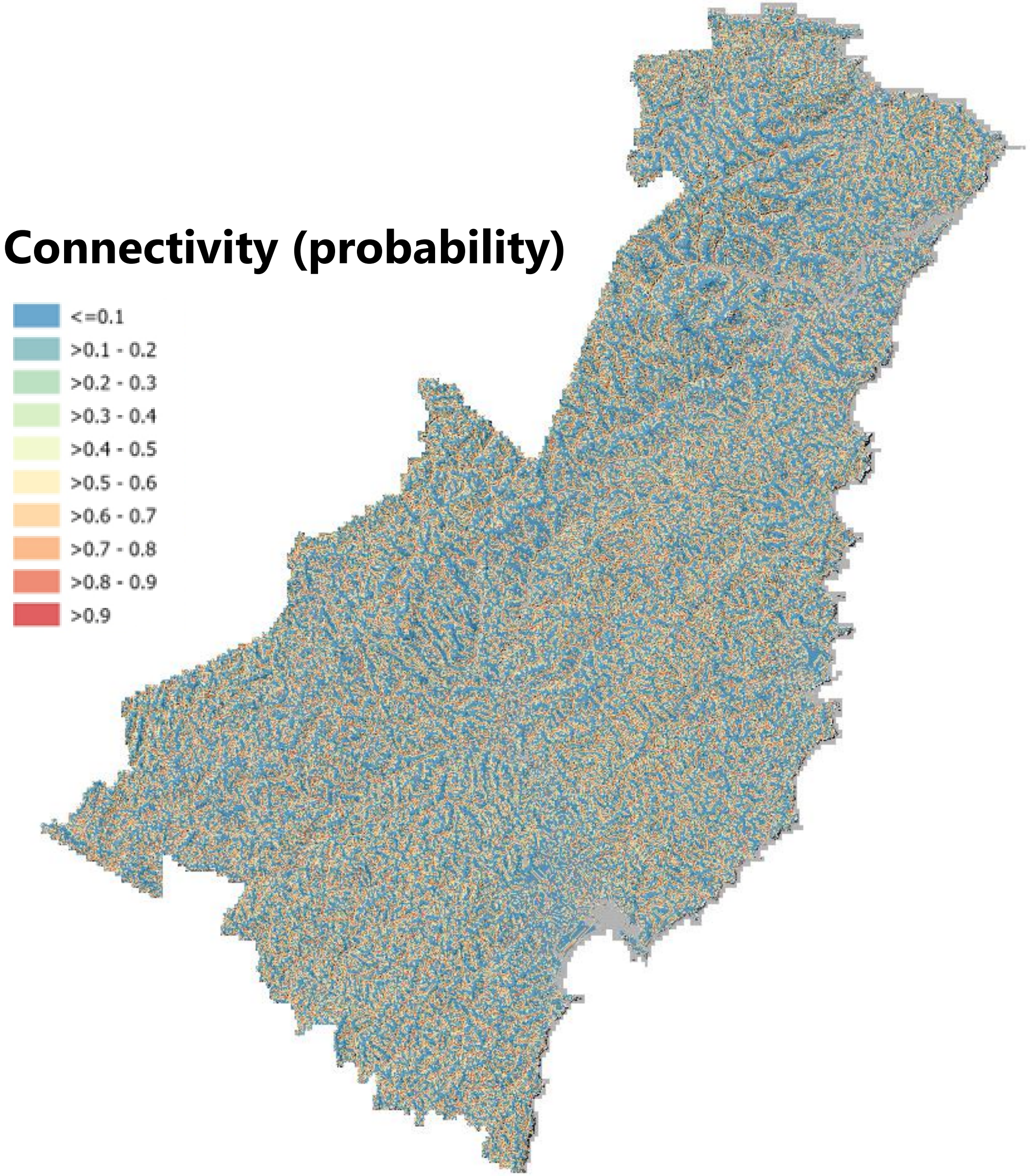


- Rank landslides in the model by their probability values in decreasing order
- Reclass probability map into ‘high’, ‘moderate’ and ‘low’ classes based on thresholds
- The choice of class thresholds is subjective

Susceptibility (Class)

Class	Percentage of mapped landslides	Probability thresholds
High	80	>0.61
Moderate	15	0.28 - 0.61
Low	5	<0.28

4.2 Landslide connectivity – from probability to class

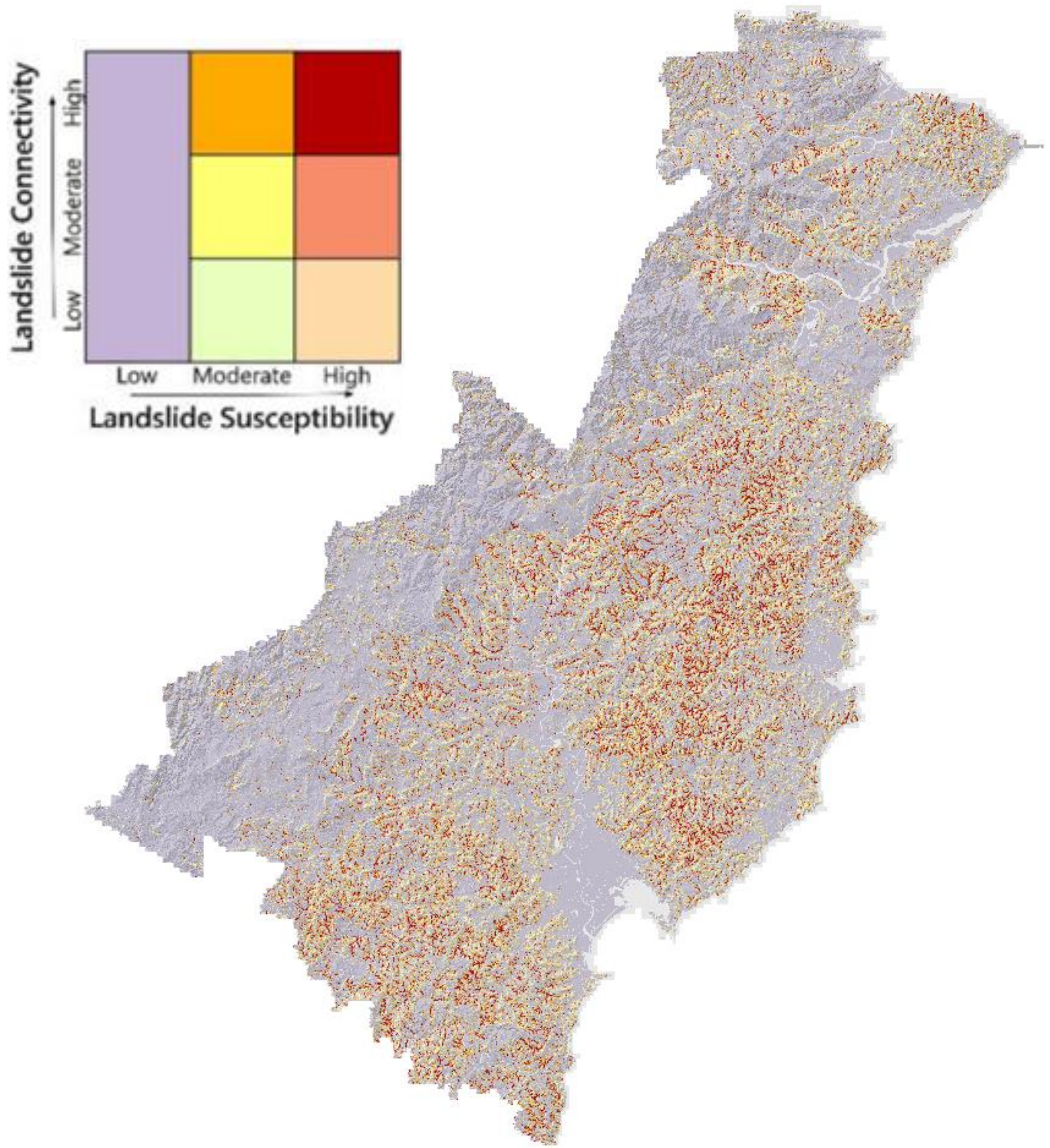


- Rank connected landslides in the model by their probability values in decreasing order
- Reclass probability map into ‘high’, ‘moderate’ and ‘low’ classes based on thresholds
- The choice of class thresholds is subjective

Connectivity (Class)

Class	Percentage of mapped connected landslides	Probability thresholds
High	80	>0.58
Moderate	15	0.18 - 0.58
Low	5	<0.18

4.3 Combining landslide susceptibility and connectivity

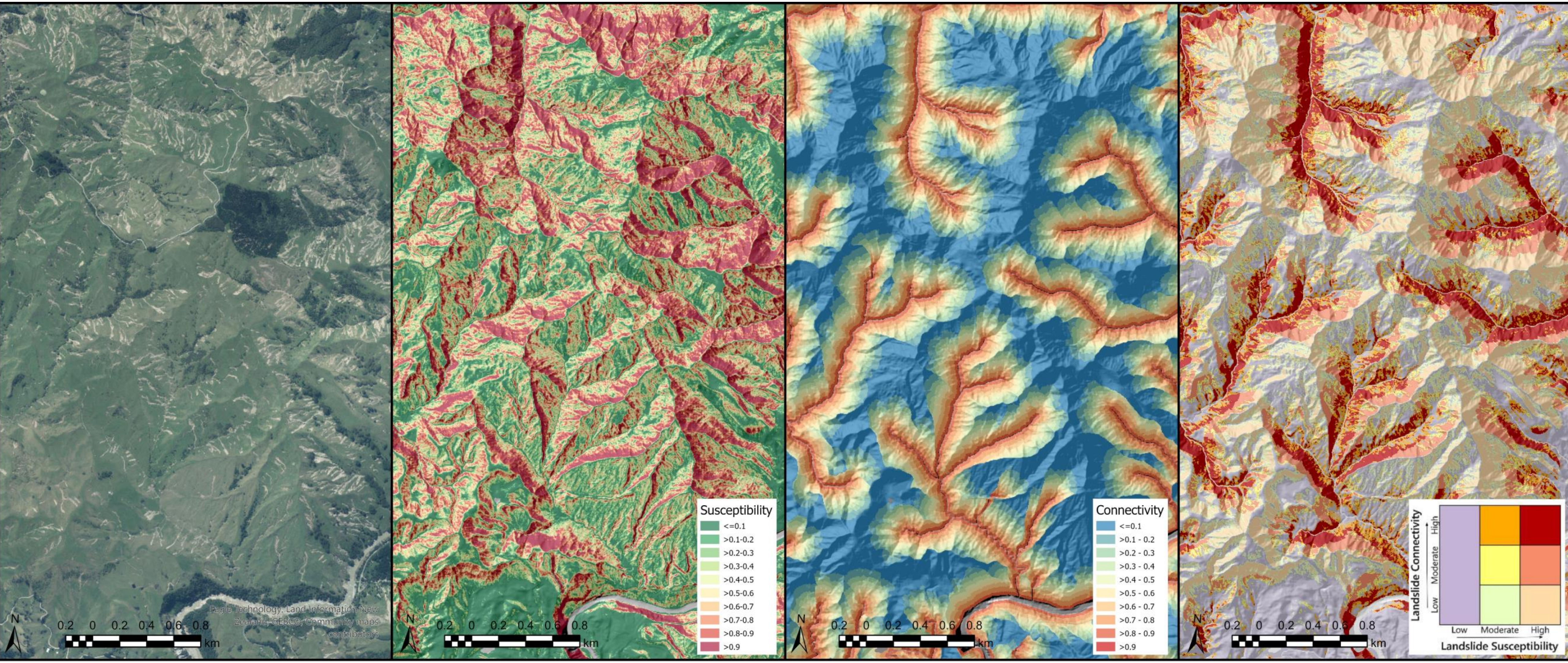


- Combine class-based landslide susceptibility and connectivity layers
- 7-class matrix defines joint susceptibility-connectivity classes

Class	Area (km^2)	Area (%)
1. Low LS	5,553	67.6
2. Mod LS / Low Con	605	7.4
3. Mod LS / Mod Con	405	4.9
4. Mod LS / High Con	398	4.8
5. High LS / Low Con	487	5.9
6. High LS / Mod Con	354	4.3
7. High LS / High Con	417	5.1

4.3 Combining landslide susceptibility and connectivity

Susceptibility (prob) **Connectivity (prob)** **Combined (class)**

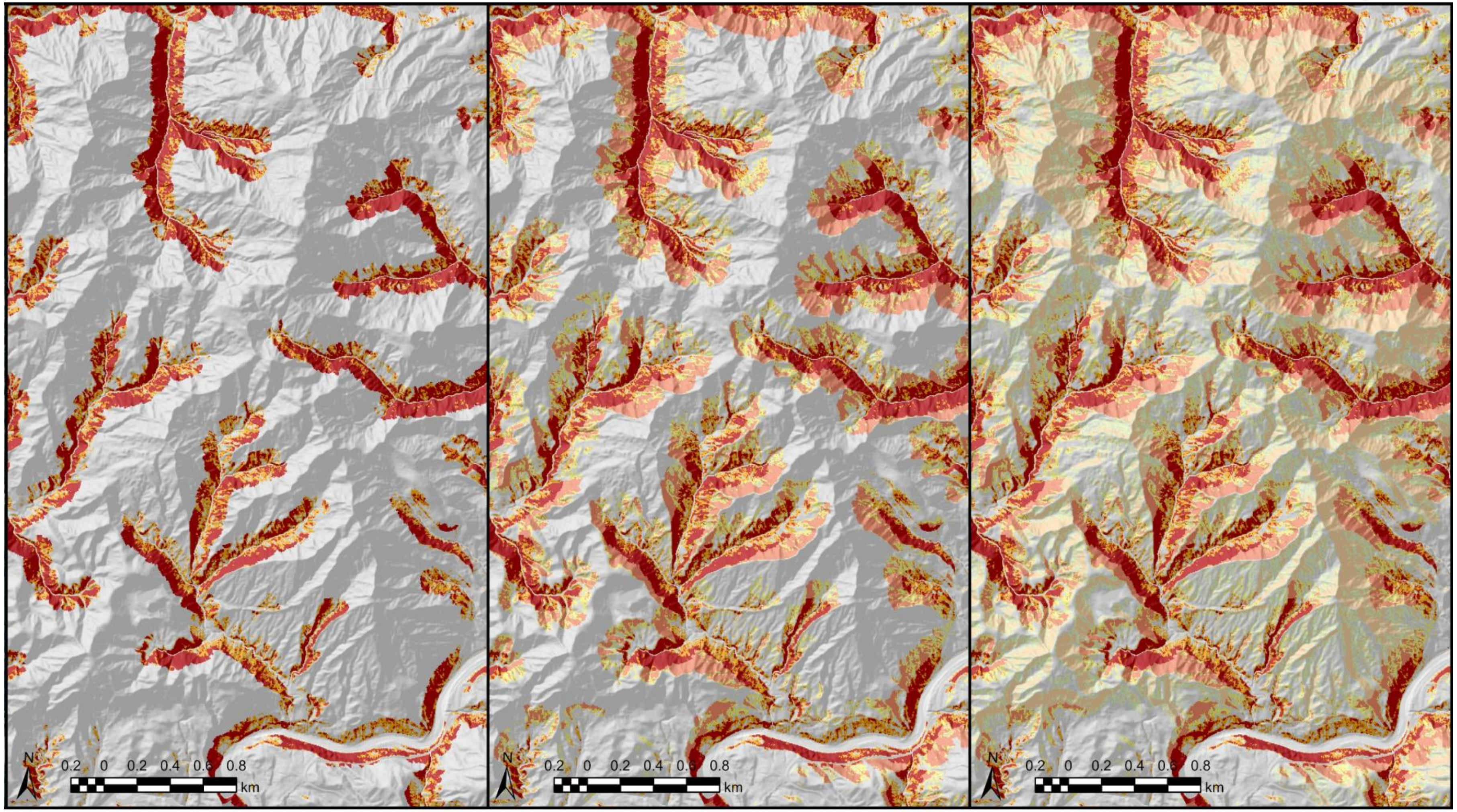


4.3 Combining landslide susceptibility and connectivity

Expect susceptible and connected areas to increase with rainfall intensity

Class

- 1. Low LS
- 2. Mod LS / Low Con
- 3. Mod LS / Mod Con
- 4. Mod LS / High Con
- 5. High LS / Low Con
- 6. High LS / Mod Con
- 7. High LS / High Con

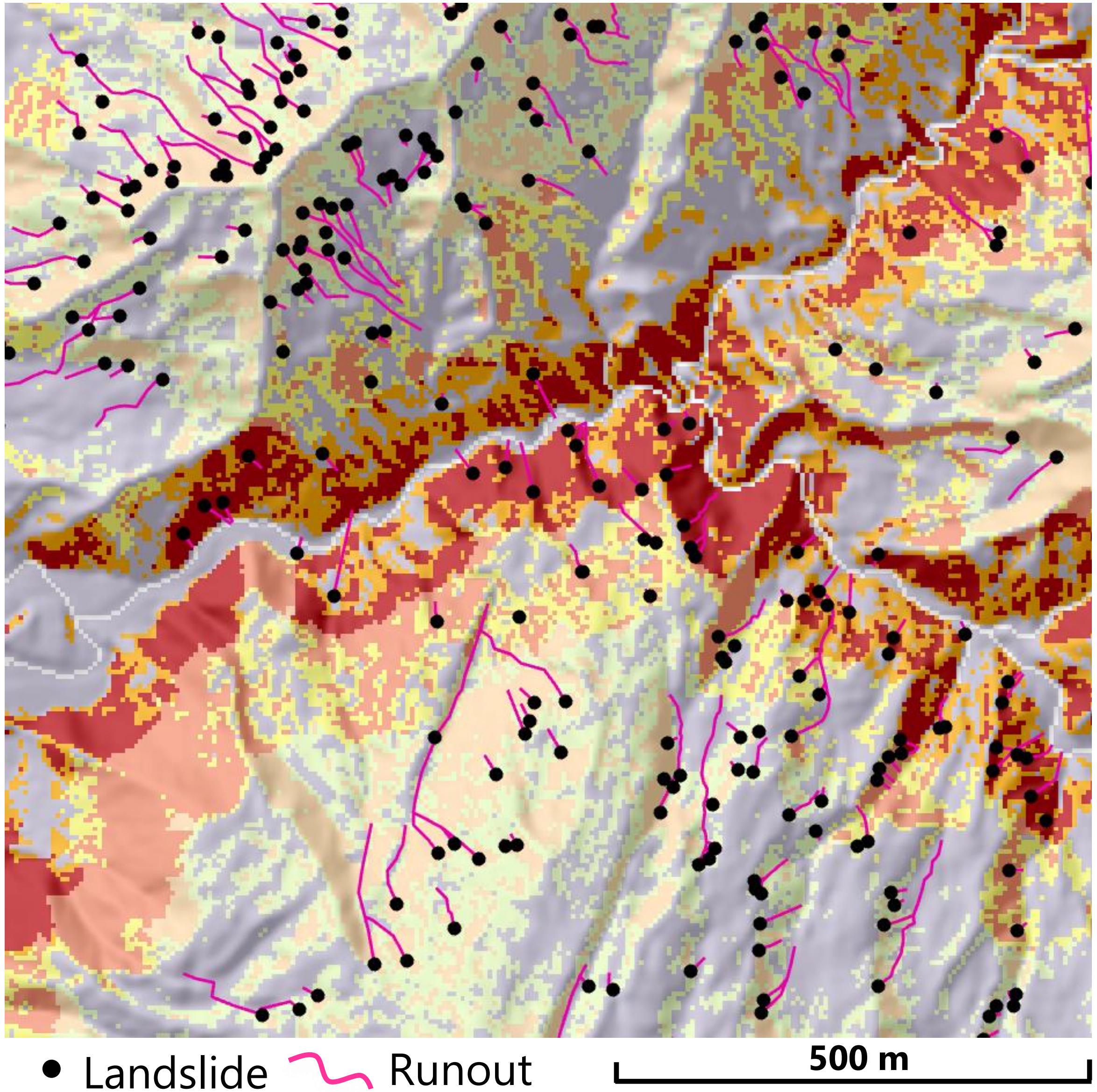


Classes displayed: [4, 7] [3, 4, 6, 7] [2, 3, 4, 5, 6, 7]

4.4 Map validation - Cyclone Gabrielle landslides

- Compared class-based maps with interim landslide data from Cyclone Gabrielle (Leith et al. 2023) – accessed January 2024
- Gabrielle data not used to train the model – an independent map validation
- Extreme rainfall triggers more landslides in ‘moderate’ and ‘low’ class areas

Class	**Susceptibility** % of all mapped landslides	**Connectivity** % of all mapped connected landslides
High	58	71
Moderate	24	18
Low	18	11



5. Key messages

- Shallow Landslide susceptibility and connectivity modelling: data-driven approaches to better target erosion control and support future land use decisions
- LiDAR is a game changer – improved model performance and higher resolution landslide susceptibility and connectivity maps
- Layers may be used at the forest or farm scale to understand how susceptibility and connectivity vary across a property to assist planning

6. Acknowledgements

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