Rapid assessment of land damage – Cyclone Gabrielle

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Rapid assessment of land damage – Cyclone Gabrielle

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Executive Summary

Cyclone Gabrielle was a severe tropical cyclone that occurred in February 2023. It caused severe landsliding in several zones along the east coast of the North Island. As part of the cyclone response, the Ministry for the Environment contracted Manaaki Whenua – Landcare Research to do a rapid assessment of the damage in hill country (Land Use Capability classes 6 and 7) resulting from the landsliding.

The extent of severe damage was large, ranging from the Gisborne district, through Hawke's Bay, and down to the Wairarapa. The total number of landslides, each typically comprising a thousand tonnes of soil, was over 300,000. This proliferation of landsliding has removed productive soil from farms and deposited sediment on floodplains. The total mass of landslides is estimated at 300 million tonnes, with an economic cost of approximately $1.5 billion (conservatively estimated at $5 per tonne of eroded soil).

The physical mechanism for landslide initiation is well understood. Intense rainfall increases the pore water pressure in the soil, which reduces the effective weight of soil at the failure plane between soil and regolith. On steep hill slopes this often results in shear stress exceeding shear strength, causing slope failure. If there is woody vegetation growing on the soil, then roots growing through the soil/regolith boundary will increase the shear strength and reduce the probability of failure. These mechanisms are generally sufficient to explain the spatial distribution of landslides in Cyclone Gabrielle; that is, landslides mostly occur where intense rainfall has fallen on steep land without protective forest cover.

The reduction in landslide probability by woody vegetation is modelled at 90% by commonly used regional soil erosion models. In the southern Hawke's Bay – northern Wairarapa hill country, this expected reduction was largely observed for both indigenous forest (90% reduction) and exotic forest (80%). However, in northern Hawke's Bay, exotic forestry was less effective than expected (60%), while indigenous forest maintained normal reduction (90%). In the Gisborne coastal hill country, exotic forestry was ineffective at reducing landslide probability, with indigenous forest resulting in only a moderate reduction (50%).

Possible causes for the low effectiveness of exotic forestry for reducing landslide probability in northern Hawke's Bay and Gisborne include:

- forestry management such as non-thinning
- multiple rotations of forestry
- thin soils caused by a long erosion history.

We recommend more detailed field investigations to determine specific causes.

In the Esk River catchment approximately 5.7 million tonnes of soil was eroded by landslides. Half of that was delivered to waterways, of which approximately 1.5 million tonnes was deposited on the flood plain of the Esk River valley at an average depth of 80 cm. If soil conservation plans had been implemented on 50% of pastoral farms in the Esk catchment, the soil eroded by landslides would have been less, at 5.3 million tonnes. If soil conservation plans had been implemented on 80% of pastoral farms in the Esk catchment, the soil eroded by landslides would have been even less, at 4.7 million tonnes, and the sediment deposited on the Esk valley floodplain would have been less at 60 cm average depth.

1 Introduction

1.1 Objective of study

Cyclone Gabrielle was a severe tropical cyclone that occurred in February 2023. It caused severe landsliding in several zones along the east coast of the North Island. As part of the cyclone response, the Ministry for the Environment contracted Manaaki Whenua – Landcare Research to do a rapid assessment of the damage caused by the landsliding.

The services required were:

1 automatic image differencing of bare ground from summer 2023 Sentinel imagery (freely available) at 10 m resolution (using pre- and post-2023 severe weather events)

2 manual mapping of areas with a low level of landslip damage (e.g. Coromandel, Bay of Plenty)

3 tidying of new bare ground image areas related to land damaged by the severe weather events (i.e. excluding clouds, ploughed paddocks or recently harvested forestry)

4 summarising land damage area by territorial/local authority zone, catchment, and land cover in the affected regions

5 assessing costs related to soil erosion based on the area damaged

6 assessing highly erodible land affected by land damage using a statistical approach.

Deliverables included two GIS raster layers:

1 a map showing landslip density due to the severe events of summer 2023 (with a pixel representing percentage damaged area within 1 km^2) in affected regions (Northland, Auckland, Waikato, Hawke's Bay, Gisborne, and parts of Manawatū and Wairarapa) at 10 m resolution

2 a map of bare ground in affected regions (Northland, Auckland, Waikato, Hawke's Bay, Gisborne, and parts of Manawatū and Wairarapa) at 10 m resolution.

The third deliverable was a report including:

1 generated maps of bare ground, illustrating land damage against land cover

2 a summary table of land damage by zone, catchment, and land cover, and the estimated costs of soil erosion (to include assumptions on sediment contribution to waterways if achievable within budget)

3 estimates of the reduction that could have been achieved if effective soil conservation farm plans had been fully implemented, including: (i) sediment reduction estimates if 30%, 50%, and 80% of the affected areas had soil conservation farm plans fully implemented; and (ii) sediment reduction estimates if the same percentages of land area (30%, 50%, and 80%) had low-cost, lower-density native planting methods for

treating highly erodible land with indigenous vegetation, with canopy closure achieved within 5–8 years (from a recent [Our Land & Water National Science Challenge-funded project](#))

4 estimates of highly erodible land affected by land damage

5 limitations of the approach, and assumptions made to create the maps and summary tables.

1.2 Methodology

Assessment of damage by detecting change based on before and after satellite images

Sentinel 2 satellite imagery for the whole of the North Island was obtained for before and after Cyclone Gabrielle (Figure 1). Sentinel 2 is a multispectral, polar-orbiting satellite constellation that provides imagery every 5 days. Manaaki Whenua – Landcare Research collects, processes, and curates the entire record of Sentinel imagery for New Zealand. Although image acquisition is comparatively frequent, obtaining entirely cloud-free imagery for a single day is generally not possible.

For this assessment, the before and after images were mosaics comprising cloud-free pixels that were selected preferentially from images acquired as close as possible in time to when the cyclone occurred. The change detection algorithm was designed to detect new bare ground appearing in the after imagery. This was achieved by finding pixels in the after imagery that had increased significantly in brightness in the visible bands.

The change detection algorithm was optimised for the detection of new bare ground due to landslide damage caused by the cyclone. However, it was also sensitive to other effects unrelated to the cyclone, such as cultivation. For this reason, the analysis focused on Land Use Capability (LUC) Classes 6 and 7 [1]; that is, steep land where most landslides occur and little cultivation occurs. To minimise any remaining false positives caused by forest harvesting or agricultural practices we visually checked the before and after imagery of all mapped damage areas larger than 3ha (871).

New bare ground associated with landsliding on steep land comprises landslide scar and debris tails. The analysis of land cover focuses on the source of the landslides – the scars. Following Dymond et al. [2] we separated out scars from tails in the new bare ground, and we lumped pixels classified as new bare ground into contiguous clumps. For each clump, the pixel with the highest elevation (in a digital elevation model) was identified and assumed to be the uppermost part of an erosion scar. The pixel with the lowest elevation was also identified, and therefore the elevation range of the clump could be calculated. All other pixels in the clump within 25% of the elevation range from the uppermost pixel were also labelled as scar.

Disaggregation of erosion damage by land cover class, territorial authority, sea draining catchments and damage zones

We analysed the incidence of landsliding as a function of land cover class using an updated version of the 2018 Version of the Land Cover Database (LCDB Version 5.0). The updates used the same methodology as the 2018 Version, based on Sentinel 2 imagery from October 2022, and accounted for:

- Harvested forest (Class 64 in 2018) that has since transitioned to Exotic Forest, and
- Exotic Forest (Class 71 in 2018) that has since been harvested.

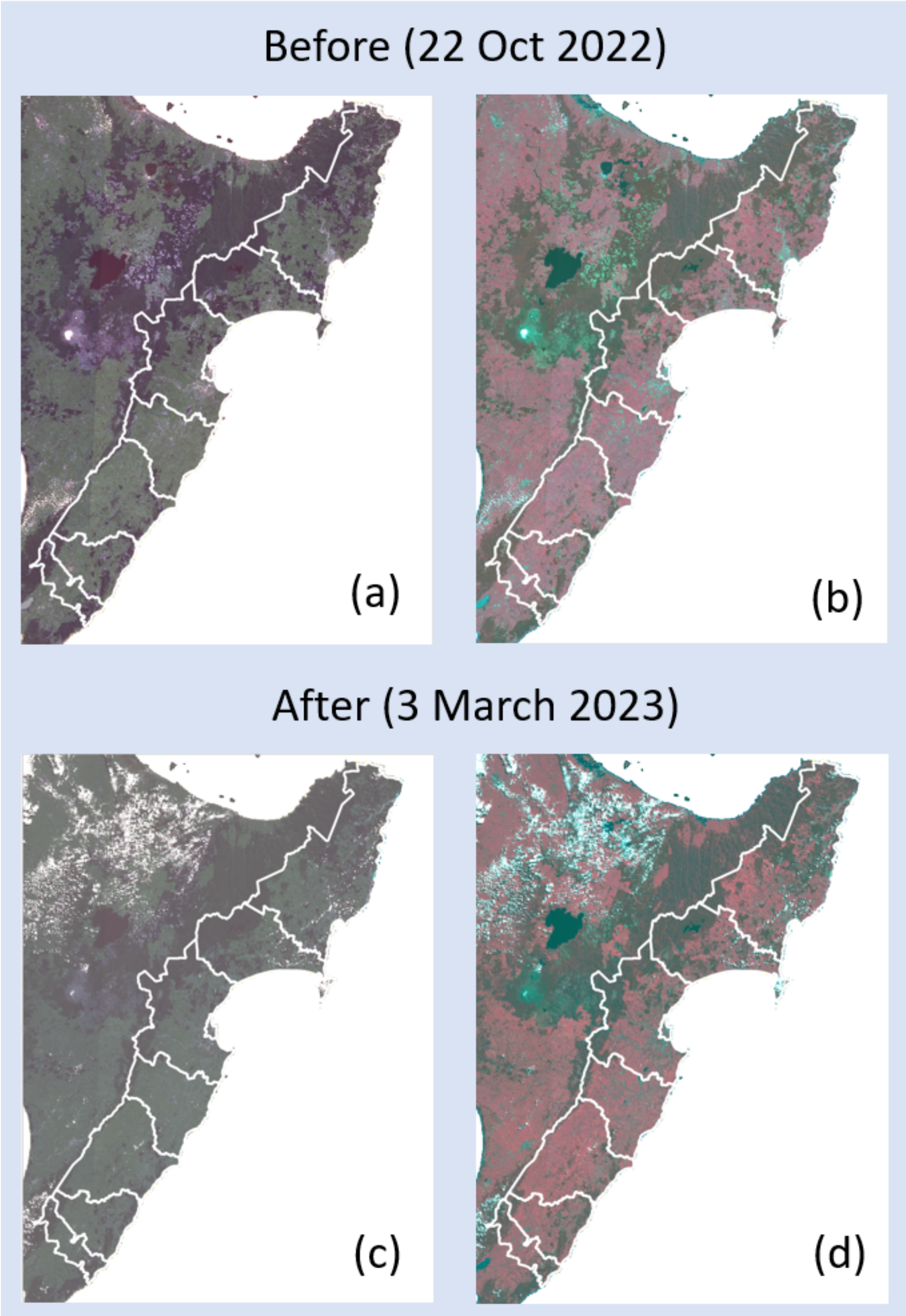

Figure 1. Sentinel 2 satellite imagery used for change detection (natural colour left and infrared right).

2 Results

Figure 2 shows a summary map of landsliding. In each square kilometre the proportion of damaged land (both landslide scar and debris tail) is calculated and coloured according to the legend. Orange and red colours show severe landsliding damage of greater than 2.5%.

Landsliding was most prevalent along the eastern coast of the North Island and severely affected seven districts: Carterton, Masterton, Tararua, Central Hawke's Bay, Hastings, Wairoa, and Gisborne. The most intense damage occurred between northern Wairarapa and districts in the Hawke's Bay and Gisborne regions.

Four areas were identified as having a markedly high intensity of landslides, and these are referred to in the following as 'landslide damage zones'. In these zones the average percentage of bare ground was as high as 5 to 10%, and in the most intensely affected areas exceeded 10%. Of the four landslide zones, the one labelled 'Northern Hawke's Bay hill country' was affected substantially more severely than the others.

Outside the mapped area in Figure 2, Cyclone Gabrielle caused landsliding in a few localised areas in Coromandel, Auckland, and Northland. These areas were manually detected and a separate shape file was created to record their location. The area under consideration (the seven districts and LUC Classes 6 and 7) comprised a total land area of 8909 km^2. Of this, landslide scars accounted for 221 km^2 (or about 0.4%).

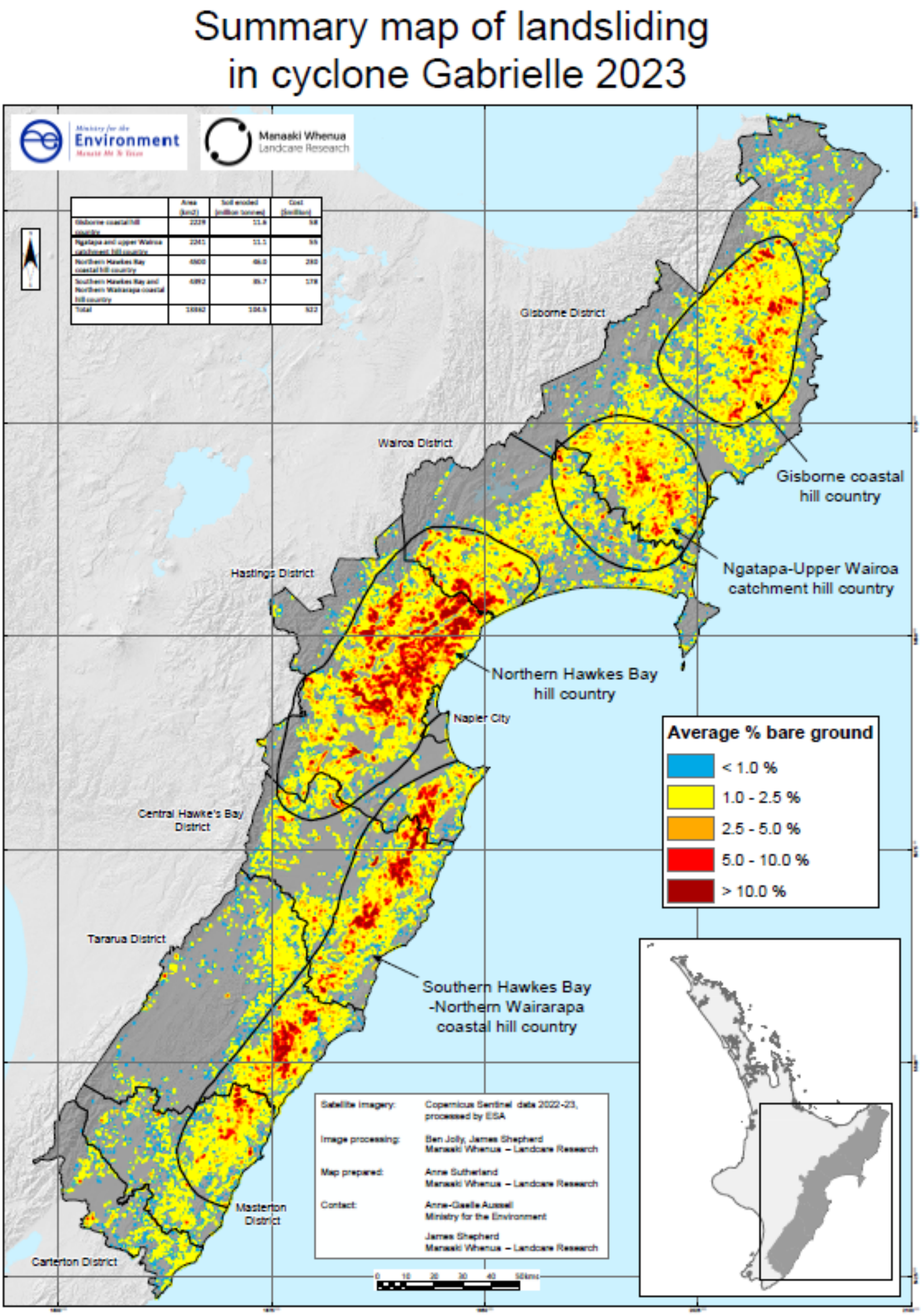

Figure 2. Summary map of landsliding. Colours show the proportion of land in each square kilometre mapped as bare (either landslide scar or debris tail).

Table 1. Area of landslide scars in different land covers, by territorial authority (km^2)

Damage zone	Broadleaved Indigenous Hardwoods	Exotic Forest	Forest - Harvested	High Producing Exotic Grassland	Indigenous Forest	Low Producing Grassland	Mānuka and/or Kānuka	Other	Total
Carterton District	0.04	0.15	0.13	1.11	0.02	0.04	0.10	0.09	**1.66**
Central Hawke's Bay District	0.23	0.48	0.25	27.54	0.17	0.32	0.34	0.93	**30.25**
Gisborne District	1.78	14.36	7.21	20.84	0.53	2.40	2.70	3.30	**53.13**
Hastings District	1.79	12.06	7.77	46.77	0.81	4.64	6.25	2.47	**82.56**
Masterton District	0.13	0.99	1.24	7.75	0.03	0.21	0.32	0.21	**10.88**
Tararua District	0.09	0.60	0.51	17.66	0.06	0.55	0.55	0.32	**20.34**
Wairoa District	0.99	5.26	1.95	10.97	0.36	1.02	1.45	1.15	**23.15**
Total	**5.04**	**33.90**	**19.07**	**132.64**	**1.98**	**9.17**	**11.71**	**8.47**	**221.97**

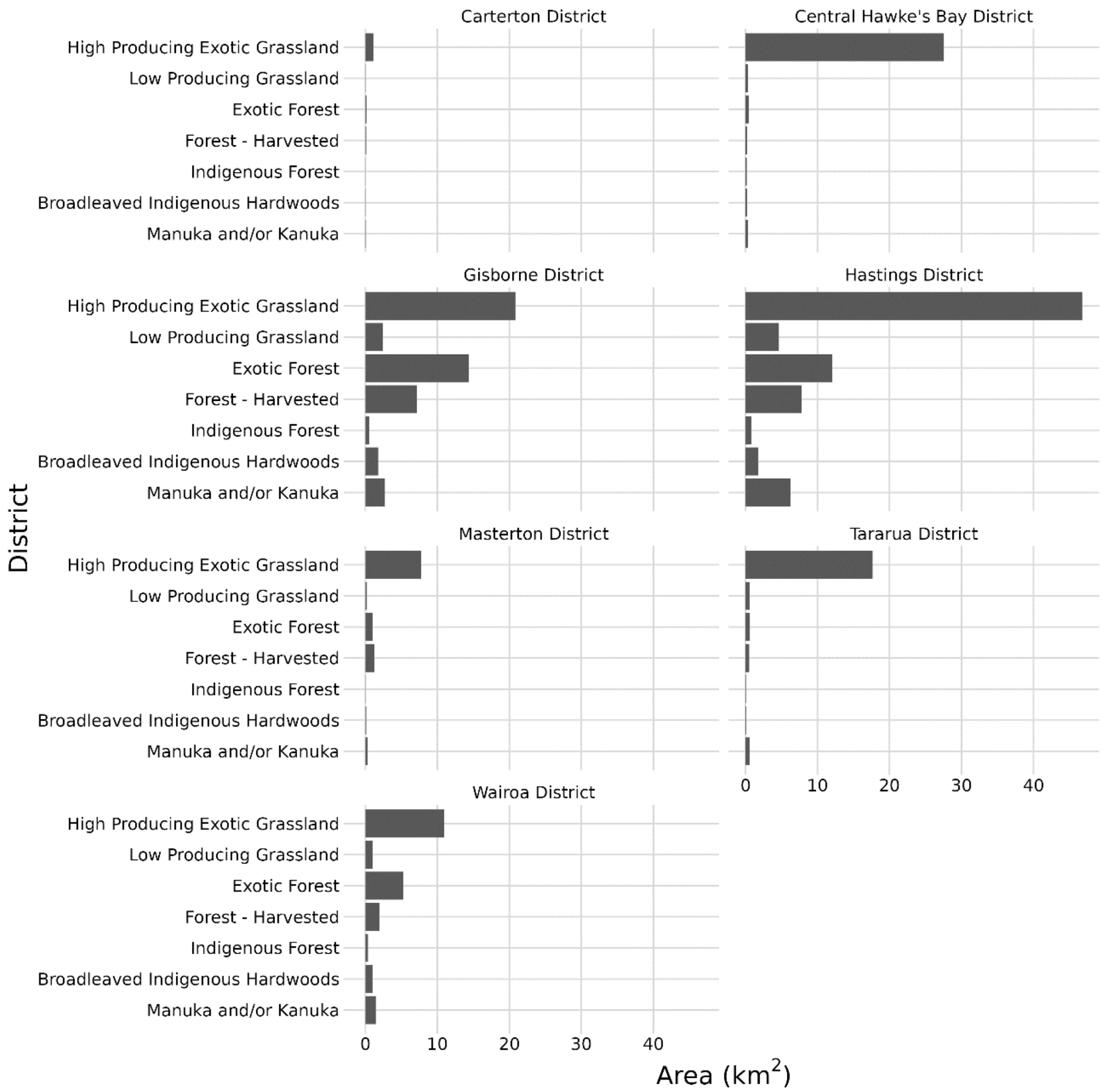

Figure 3. Area of landslide scars in different land covers, by territorial authority (km^2).

In terms of landslide scar area, Hastings District suffered the greatest damage with 83 km^2, mostly occurring on high-producing exotic (HPE) grassland (Table 1, Figure 3), although substantial landslide scars also occurred on exotic forest and harvested forest. Across the other districts, HPE grasslands also experienced the greatest amount of landsliding (in terms of total area). Exotic forest was disproportionately low as a source of landslides in the five southern districts but was disproportionately high in the two northern districts (Wairoa and Gisborne). Harvested forest was also a disproportionately high source of landslides in the two northern districts. Only minor amounts of landsliding occurred on areas covered with indigenous forest, broadleaved indigenous hardwoods, and mānuka/kanuka (Figure 3).

The major sea-draining catchments accounted for 11,417 km^2 (or 19%) of the total LUC Class 6 and 7 land area (60,600 km^2) within the seven districts (Table 2, Figure 4). In all except the Ūawa catchment, HPE grassland accounted for the major share of landsliding. In the Akitio, Pōrangahau and Tukituki catchments, HPE grassland accounted for 70 to 79% of all the land cover but suffered between 87 and 93% of all scarring.

Table 2. Area of landslide scars in different land covers, by major catchment (km^2)

Damage zone	Broadleaved Indigenous Hardwoods	Exotic Forest	Forest - Harvested	High Producing Exotic Grassland	Indigenous Forest	Low Producing Grassland	Mānuka and/or Kānuka	Other	Total
Ākitio	0.01	0.04	0.07	2.92	0.01	0.02	0.04	0.04	**3.15**
Esk	0.02	0.61	1.05	1.42	0.01	0.13	0.55	0.04	**3.83**
Mohaka	0.35	1.22	0.35	1.65	0.13	0.51	0.44	0.20	**4.86**
Ngaruroro	0.45	1.08	0.65	6.45	0.14	0.22	0.99	0.51	**10.50**
Pōrangahau	0.02	0.06	0.03	2.95	0.00	0.03	0.09	0.04	**3.22**
Tukituki	0.06	0.11	0.37	7.02	0.06	0.15	0.03	0.29	**8.09**
Tūtira	0.03	0.32	0.27	1.10	0.01	0.17	0.08	0.02	**1.99**
Ūawa	0.02	1.34	0.62	0.34	0.00	0.11	0.14	0.06	**2.64**
Waiapu	0.28	1.00	0.37	1.06	0.11	0.41	0.29	0.48	**4.00**
Waipaoa	0.11	0.79	1.27	2.24	0.01	0.11	0.23	0.23	**5.00**
Wairoa	0.17	0.35	0.69	3.92	0.08	0.18	0.39	0.33	**6.11**
Total	**1.52**	**6.93**	**5.75**	**31.08**	**0.57**	**2.03**	**3.27**	**2.23**	**53.39**

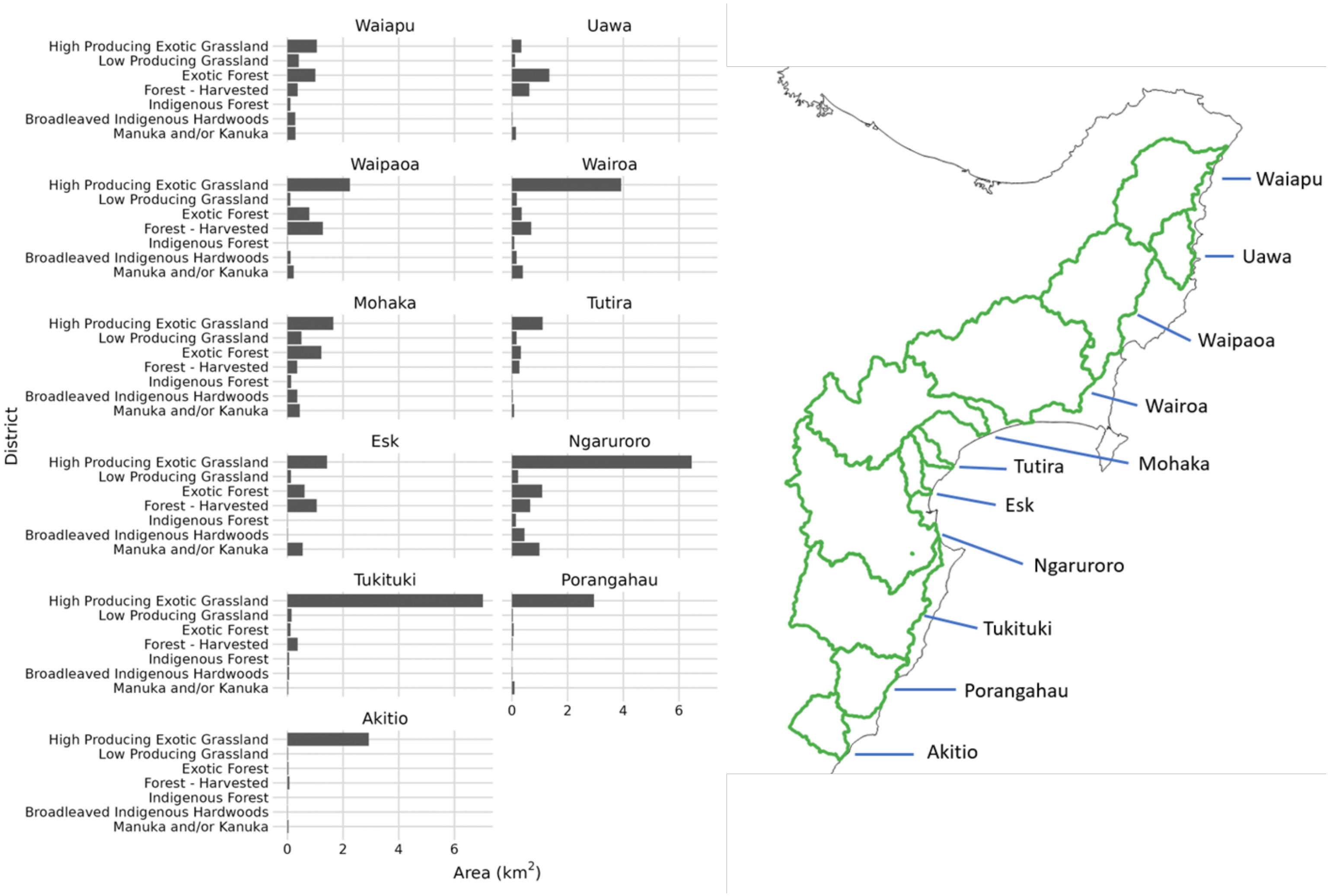

Figure 4. Areas of landslide scars in different land covers, by major catchment.

Table 3. Area of landslide scars in different land covers, by damage zone (km^2)

Damage zone	Broadleaved Indigenous Hardwoods	Exotic Forest	Forest - Harvested	High Producing Exotic Grassland	Indigenous Forest	Low Producing Grassland	Mānuka and/or Kānuka	Other	Total
Gisborne coastal hill country	0.31	3.18	2.00	1.99	0.08	0.59	0.51	0.56	9.22
Ngātapa – Upper Wairoa catchment hill country	0.14	0.72	0.94	4.41	0.05	0.13	0.30	0.34	7.02
Northern Hawke's Bay hill country	0.92	4.59	3.61	15.68	0.30	1.67	2.26	0.84	29.86
Southern Hawke's Bay – northern Wairarapa coastal hill country	0.07	0.39	1.03	16.85	0.03	0.36	0.36	0.36	19.47
Total	**1.44**	**8.88**	**7.58**	**38.93**	**0.46**	**2.74**	**3.43**	**2.10**	**65.57**

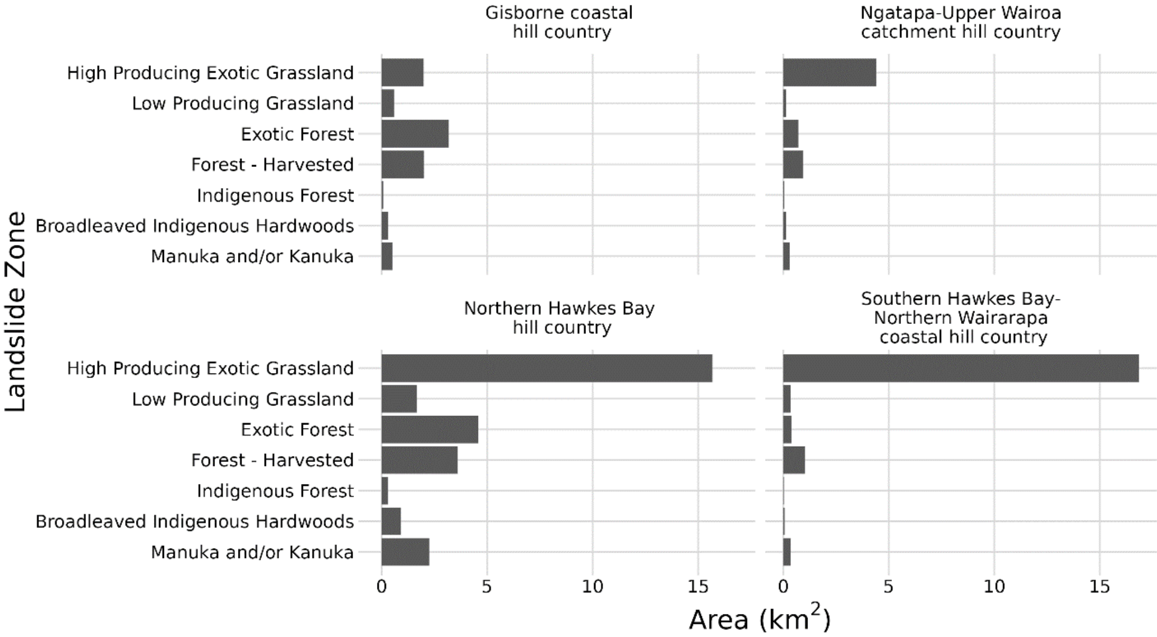

Figure 5. Total area of landslide scars in different land covers, by damage zone.

The landslide damage zones (the four areas demarcated as high landslide density zones) comprised 18% of the overall area but 30% of the landslide scars (Table 3, Figure 5). In the two southernmost landslide zones (northern Hawke's Bay and southern Hawke's Bay – northern Wairarapa), HPE grassland was responsible for most landslide scarring, whereas in the two northern landslide zones (Ngātapa – upper Wairoa and Gisborne coastal), the relative importance of HPE grassland was smaller. This largely reflects the fact that HPE is a smaller share of the overall land cover in the two northern landslide zones compared to the two southern zones.

The analysis so far has only considered the total areas of landslide scars, but not in the context of the overall area of each land cover / land use. The following analysis considers the proportion of land within each land-cover class and disaggregation method (by territorial authority, major catchment, and landslide zone). This permits an estimation of landslide probability.

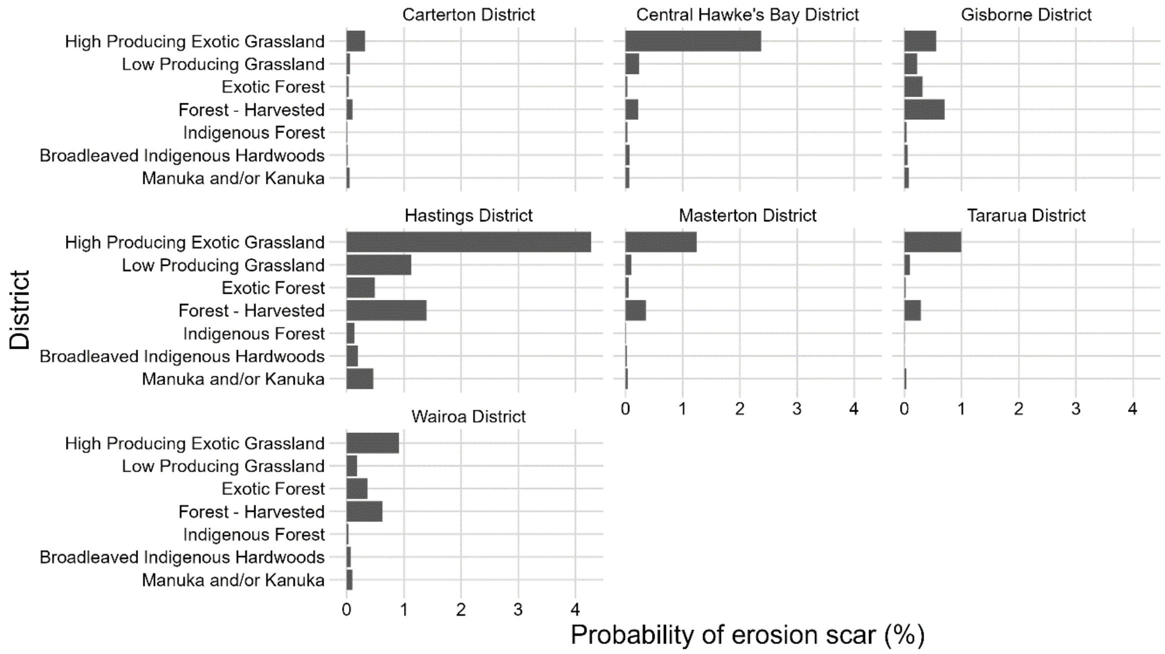

Figure 6. Probability of landsliding, by territorial authority. The probability of an erosion scar is defined as the area of erosion scars as a proportion of total land area within each land cover class/territorial authority disaggregation.

Figure 6 shows the probability of landsliding by territorial authority. HPE has the highest probability of landsliding, with a probability of over 4% in the Hastings District and over 2% in the Central Hawke's Bay District. In all districts, the probability of landsliding is highest for HPE, except for Gisborne, where it is exceeded by forest-harvested. The probability of landsliding for exotic forest ranges between 0.3% and 0.6% for the Hastings, Wairoa, and Gisborne districts.

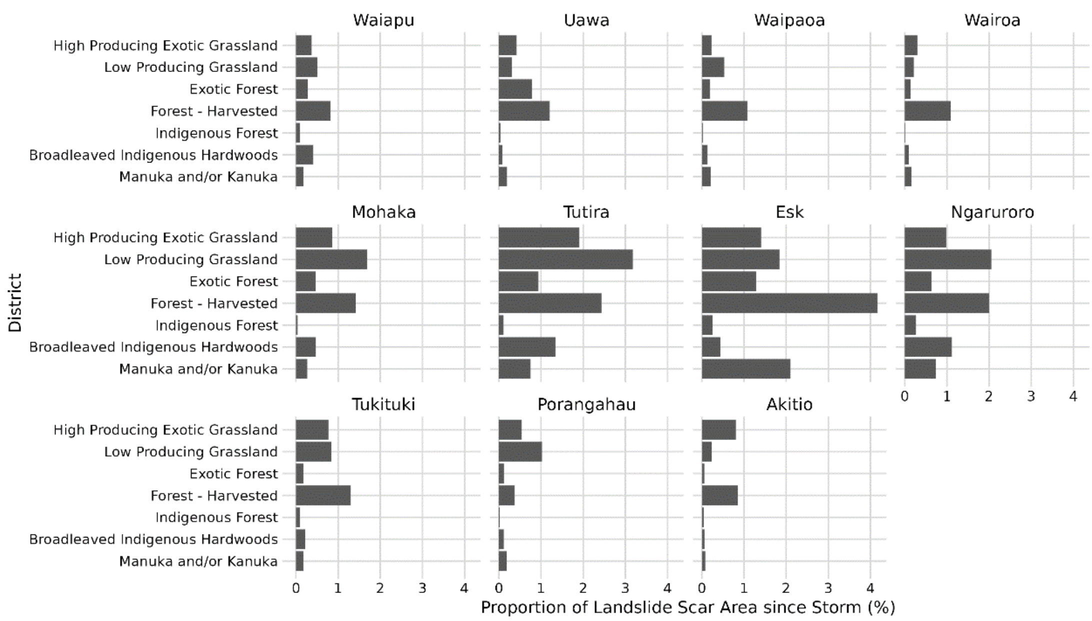

Figure 7. Probability of landsliding, by major catchment. The probability of an erosion scar is defined as the area of erosion scars as a proportion of total land area within each land cover class/catchment disaggregation.

Figure 7 shows the probability of landsliding by major catchment. The Esk River catchment has a high probability of over 4% for forest-harvested. The Ngaruroro catchment has a high probability of over 2% for both forest-harvested and low-producing grassland, and Tūtira has a high probability of over 3% for low-producing grassland and over 2% for forest-harvested.

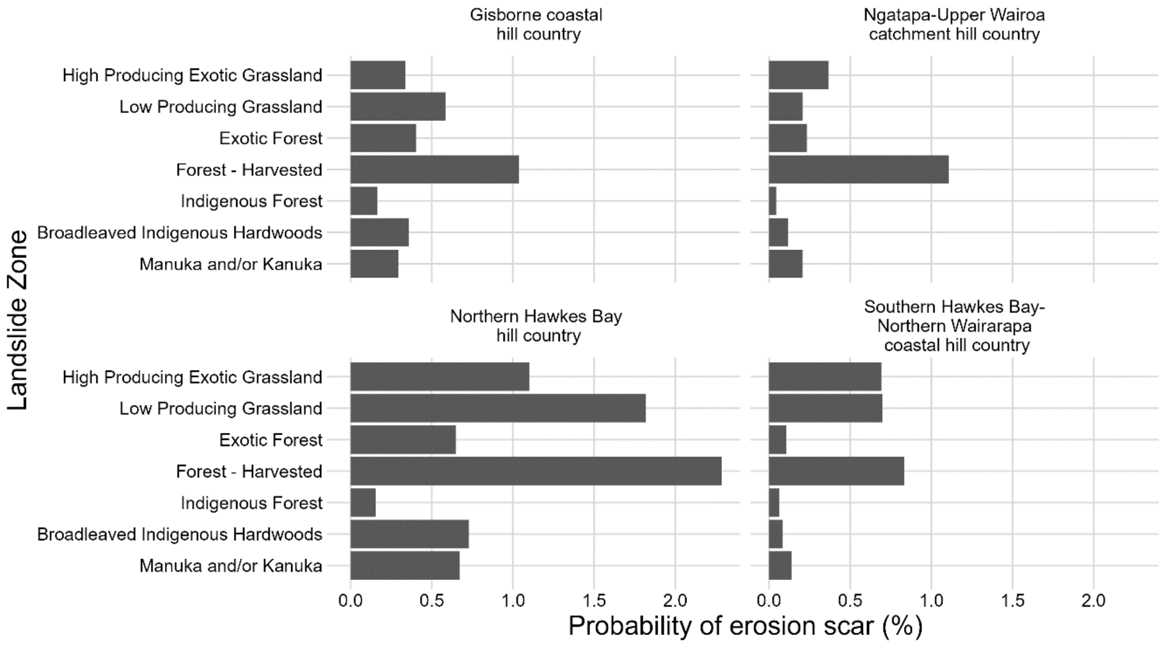

Figure 8. Probability of landsliding, by damage zone. The probability of an erosion scar is defined as the area of erosion scars as a proportion of total land area within each land cover class/damage zone disaggregation.

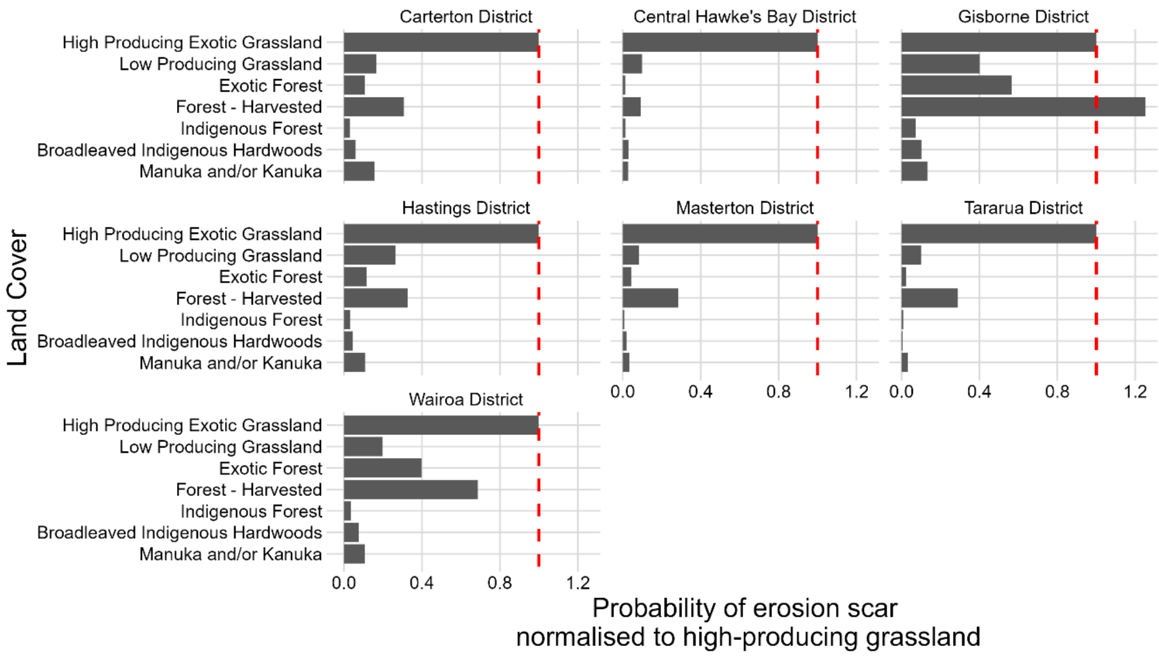

Figure 9. Probability of landsliding relative to high-producing exotic grassland, by territorial authority.

Figure 8 shows the probability of landsliding in the landslide damage zones and highlight the high susceptibility of grassland and harvested forest to landsliding, but the much lower probability in indigenous forest. Figure 9 shows the probability of landsliding relative to HPE, by territorial authority.

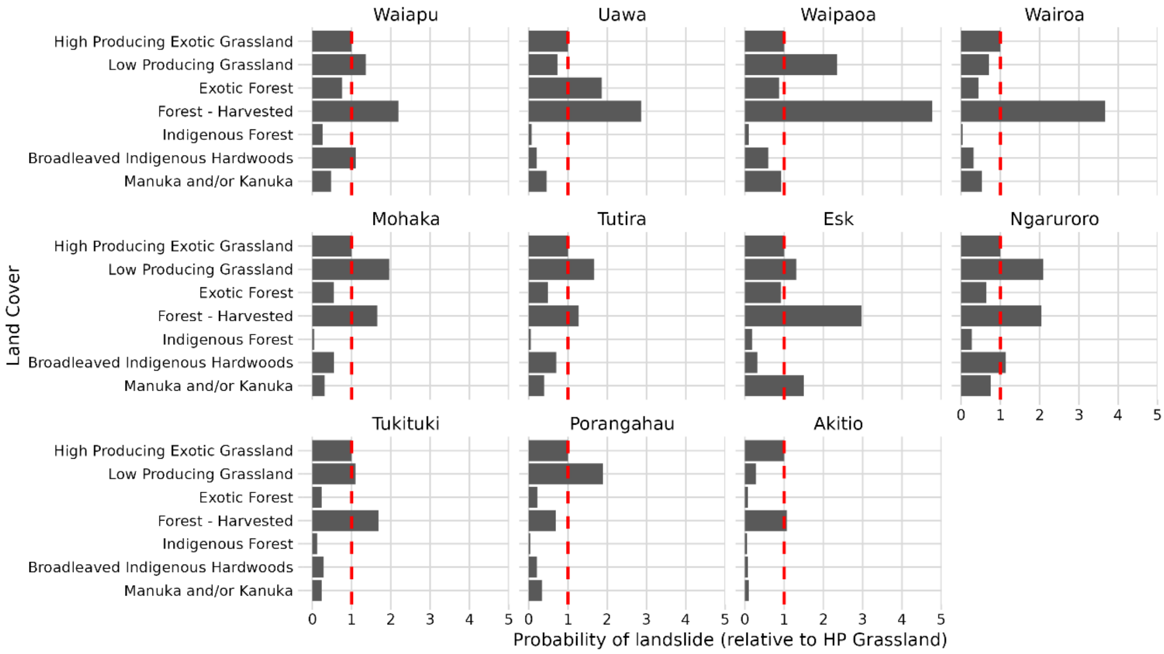

Figure 10. Probability of landsliding relative to high-producing exotic grassland, by major catchment.

Figure 10 shows the probability of landsliding relative to HPE grassland, by major catchment. In general, the only land cover that was more susceptible to landsliding than HPE grassland, was low-producing grassland and forest harvested. However, some notable exceptions occurred in the Esk catchment, where mānuka/kanuka was roughly 50% more susceptible, and in the Ngaruroro and Waiapu catchments, where broadleaved indigenous hardwoods were more susceptible than HPE grassland.

The explanation for the high susceptibility of mānuka/kanuka areas may be partly lithological. We analysed erosion susceptibility on broad classes of rock (derived from the "toprock" attribute of the Land Resource Inventory Edition 2) across the study area. The analysis indicated that sandstone, followed by mudstone, were the broad rock classes that were most susceptible to landsliding (Appendix 3, Figure A4).

The Esk catchment has uniquely high proportions of sandstone compared to other catchments (Appendix 3, Figure A5), and particularly in areas where the land cover class is mānuka/kanuka. In the Esk catchment, the proportion of sandstone comprises more than 90% of the rock type underlying mānuka/kanuka stands.

It is likely that these lithological factors, combined with the greater rainfall intensity in the Esk catchment, may have combined to cause the high landslide density on mānuka/kanuka areas. and the incomplete canopy development [13]. In addition, the incomplete closure of the canopy may have been a contributing factor [8,9,11].

Following similar logic, the high landsliding susceptibility of broadleaved indigenous hardwoods in the Ngaruroro catchment could be explained by the relatively high proportion of sandstone underlying this land cover class. However this does not hold true for the Waiapu catchment, which is dominated by mudstone and argillite (Appendix 3, Figure A5) and a more multifaceted explanation would need to be invoked. Such an explanation would involve consideration of the root tensile strength of the particular vegetation in these catchments [12], stand age [10], and slope.

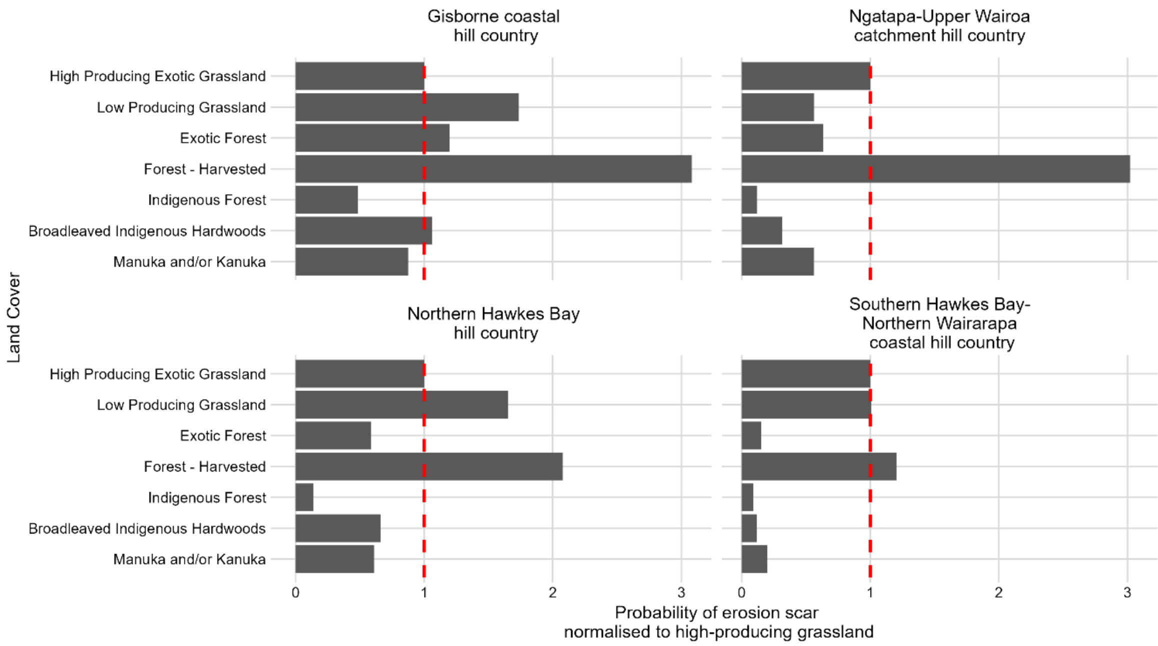

Figure 11. Probability of landsliding relative to high- producing exotic grassland, by damage zone.

Figure 11 shows the probability of landsliding relative to HPE by landsliding damage zone. In the southern Hawkes Bay – northern Wairarapa coastal hill country, the relative landsliding probability of exotic forest is low at 0.2, with the relative probability of indigenous forest even lower at 0.1. In the Gisborne coastal hill country, the relative probability of exotic forest is high at over 1.0, with the relative probability of indigenous forest moderately high at 0.5. The relative probability of forest-harvested in the Gisborne coastal hill country is very high at over 3.

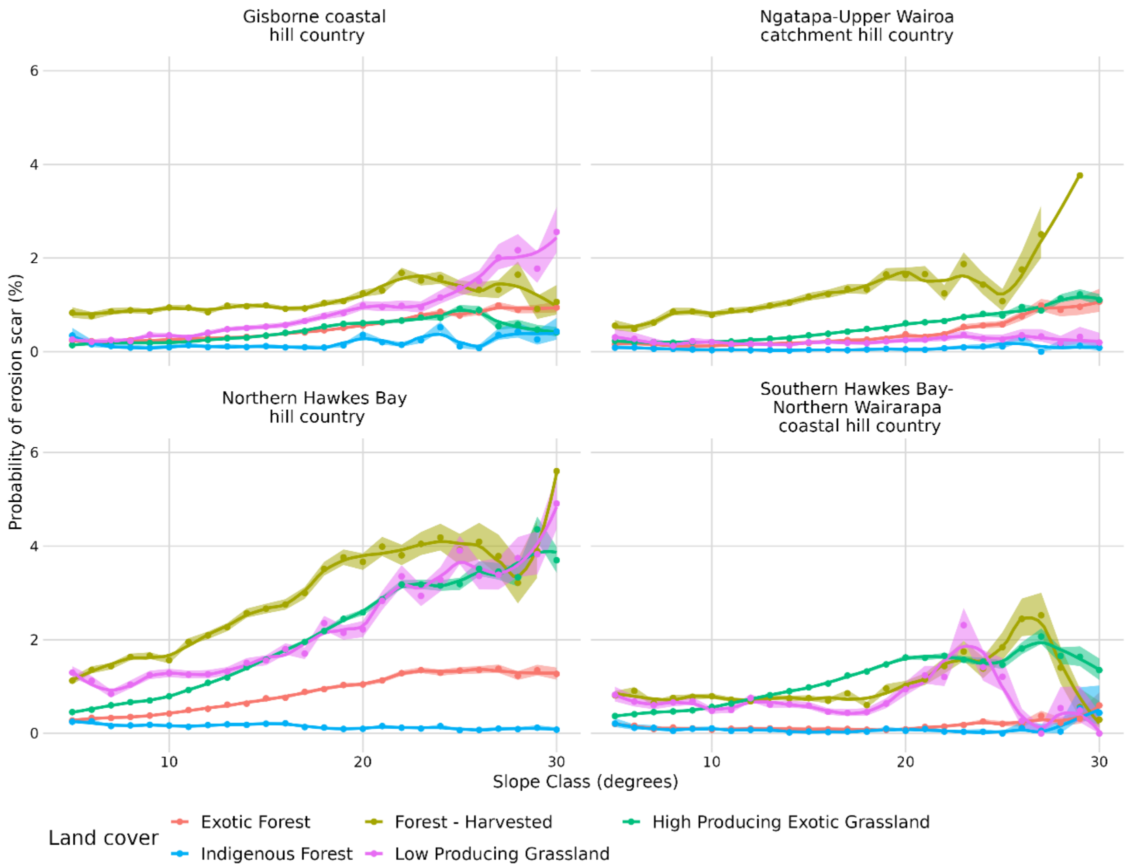

Figure 12. Probability of landsliding as a function of slope for damage zones. The shaded areas are 95% confidence intervals (Wilson Score Interval for a binomial distribution).

Figure 12 shows the probability of landsliding as a function of slope for the four landslide damage zones. Landsliding probability generally increased with increasing slope for all land cover types except in indigenous forest. However, in some cases, on slopes steeper than 22 degrees, the probability of landslides decreased with landsliding. There are several possible explanations for this result: first, only a small area of land was contained within these steeper slope categories, leading to increased uncertainty in the probability estimate (as indicated by the width of the confidence intervals); second, false negative errors in the detection of newly bare ground may have increased as a function of slope; third, projection errors increase as a function of slope, compounding uncertainty.

Given the increased uncertainty in the probability estimates of landsliding at slopes greater than 22 degrees, we focus below on comparing land cover within the different landslide zones at slopes less than 22 degrees. The trends in landslide probability on slopes greater than 22 degrees should be viewed with caution.

In the worst-hit zone, northern Hawke's Bay hill country, on 20 degree slopes, the probability of landsliding for both high-producing and low-producing grassland is high at 3.8%, for exotic forest it is 1.0% (i.e. 60% less than grassland), for indigenous forest it is low at 0.1% (i.e. 97% less than grassland), and for forest-harvested it is very high at 3.5%.

In the southern Hawkes Bay – northern Wairarapa hill country, on 20 degree slopes, the probability of landsliding for high-producing grassland is high at 1.6%, for exotic forest and indigenous forest, it is less than 0.1% (i.e. 80% less than high-producing grassland), for indigenous forest it is < 0.1% (i.e. 90% less than high-producing grassland), and for forest-harvested it is 1.0% (i.e. similar to high-producing grassland).

In Gisborne coastal hill country, on 20 degree slopes, the probability of landsliding was 1.2% for harvested forest and 1.0% for low-producing grassland. High-producing grassland and exotic forest had similar probabilities (0.6%), while indigenous forest had the lowest probability (0.4%). It should be noted that, although the susceptibility of exotic forest was roughly to that of high-producing grassland within this zone, it was lower than the susceptibility of exotic forest in the northern Hawke's Bay hill country.

In Ngatapa-Upper Wairoa Catchment hill country, the probability of landsliding in harvested forest (1.6%) was twice as likely as on any other land cover. High-producing exotic grassland had a probability of 0.6% and indigenous forest was less than 0.05%.

These results highlight the resistance of indigenous forest to landsliding and the comparative susceptibility of harvested forest across all slope types. High producing grassland tended to be more susceptible than exotic forest except in Gisborne coastal hill country.

3 Discussion

Cyclone Gabrielle caused widespread damage to land through landsliding. This report has described a rapid assessment of that damage using a remote sensing approach that detected newly bare areas. This approach was intended to be rapid and broad scale, rather than comprehensive and detailed. The following provides a discussion of the impacts of the damage, followed by a section describing the assumptions and limitations that are involved in this assessment.

3.1 Damage impacts

The extent of severe damage was large, ranging from the Gisborne district, through Hawke's Bay, and down to the Wairarapa. The total number of landslides, each typically comprising a thousand tonnes of soil, was over 300,000. The proliferation of landsliding has removed productive soil from farms and deposited sediment on floodplains. The total mass of landslides is estimated at 300 million tonnes, with an economic cost of approximately $1.5 billion (conservatively estimated at $5 per tonne of eroded soil [3]).

The physical mechanism for landslide initiation is well understood [4]. Intense rainfall increases the pore water pressure in the soil, which reduces the effective weight of soil at the failure plane between soil and regolith. On steep hill slopes this often results in shear stress exceeding shear strength, causing slope failure. If there is woody vegetation growing on the soil, then roots growing through the soil–regolith boundary will increase the shear strength and reduce the probability of failure [8-12]. These mechanisms are generally sufficient to explain the spatial distribution of landslides in Cyclone Gabrielle; that is, landslides occur mostly where intense rainfall has fallen on steep land without protective forest cover.

The reduction in landslide probability by woody vegetation is modelled at 90% by commonly used regional soil erosion models [5,6]. In southern Hawke's Bay – northern Wairarapa hill country, this expected reduction was largely observed for both indigenous forest (90% reduction) and exotic forest (80% reduction). However, in northern Hawkes Bay, exotic forestry was less effective than expected (60%), while indigenous forest maintained normal reduction (90%). In the Gisborne coastal hill country exotic forestry was ineffective at reducing landslide probability, with indigenous forest having only a moderate reduction (50%).

Possible causes for the low effectiveness of exotic forestry for reducing landslide probability in northern Hawke's Bay and Gisborne include:

- forestry management such as non-thinning
- multiple rotations of forestry
- thin soils caused by a long erosion history.

We recommend more detailed field investigations, and spatial as in [13] but with distinction between exotic and indigenous forest, to determine specific causes.

In the Esk River catchment, approximately 5.7 million tonnes of soil was eroded by landslides. Half of that was delivered to waterways [7], of which approximately 1.5 million tonnes was deposited on the flood plain of the Esk River valley at an average depth of 80 cm. If soil conservation plans had been implemented on 50% of pastoral farms in the Esk catchment, the soil eroded by landslides would have been less, at 5.3 million tonnes [5]. If soil conservation plans had been implemented on 80% of pastoral farms in the Esk catchment, the soil eroded by landslides would have been even less at 4.7 million tonnes, and the sediment deposited on the Esk valley floodplain would have been less at 60 cm average depth (these scenario estimates assume that currently 30% of farms have implemented soil conservation plans).

3.2 Correspondence to Highly Erodible Land (HEL)

A recent map of Highly Erodible Land (HEL) was made by intersecting a recent woody layer [2] (2022/23 summer, 10m pixels) with the erosion risk layer [2] (10m pixels). HEL land is defined as steep land (defined in the erosion risk layer) which does not have protection of woody roots (defined in the woody layer). The areas of landslide scars occurring on erosion risk and non-erosion risk land are shown in Table A-4 in Appendix 2. The accuracy of the erosion risk layer to define areas of land susceptible to landsliding (independent of the land cover factor whose accuracy is assessed elsewhere in the discussion) may be estimated from the probability of landsliding on erosion risk land relative to that on non-erosion risk land. The accuracies are 81%, 77%, 76%, 83% (i.e. probability ratios of 4.2, 3.3, 5.4, and 4.8 for non-woody) for Gisborne coastal hill country, Ngatapa - Upper Wairoa catchment hill country, Northern Hawkes Bay hill country, Southern Hawkes Bay – Northern Wairarapa coastal hill country respectively. The accuracies are sufficiently high for the HEL model to be useful for deriving regional or catchment statistics to guide land-use policy. However, the definition of mitigating woody vegetation may need to be modified in the Gisborne district where mature exotic forest was found not to be effective for reducing the occurrence of landslides in cyclone Gabrielle.

In the Esk catchment, if mature indigenous forest had been on all the HEL land (with no change of land cover on non-HEL land) then the mass of eroded soil would have reduced from 5.7 million tonnes to 4.0 million tonnes and the average depth of deposited sediment on the flood plain would have reduced from 80 cm to 50 cm (~ 30% reduction). If there was indigenous forest on HEL land and 80% of non-HEL land had soil conservation plans, then the mass of eroded soil would have reduced from 5.7million tonnes to 2.8 million tonnes and the average depth of deposited sediment on the flood plain would have reduced from 80 cm to 40 cm (~ 50% reduction).

3.3 Assumptions and limitations

This rapid scale assessment was achieved by detecting newly bare ground in satellite imagery before and after the cyclone event. A key assumption involved in this assessment was that the change in ground cover was caused by the cyclone. However, the detection of newly-bare areas in LUC Classes 1 to 5 was contaminated by agricultural cultivation, which could be mistaken for damage due to the cyclone. LUC Class 8 land was also subject to spurious detection of damage due to natural erosion processes. For these reasons, only LUC Classes 6 and 7 were included in the analysis. LUC Classes 6 and 7 represented 70 percent of the total area within the 8 territorial authorities that were the domain of this study. LUC Class 8 land was primarily in mountain ranges where the storm rainfall was less than the coastal hill country and as a result received no landsliding.

The comparatively coarse resolution of the Sentinel 2 imagery (10 m) does not provide the level of resolution to accurately partition bare areas into erosion scars and tails for single landslides. However, for broad scale analysis as presented it is sufficient. Fine scale analysis involving individual scars was beyond the scope of this project, but is being pursued in other, ongoing studies. The heuristic approach undertaken here, by assuming that the erosion scar component occurs in the 25 percent of pixels in the damaged area with the highest elevations relied on previous work [2] and was supported by visual inspection of a selection of erosion scars.

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Appendix 1 – Total areas of different land-cover types on LUC Classes 6 & 7 land

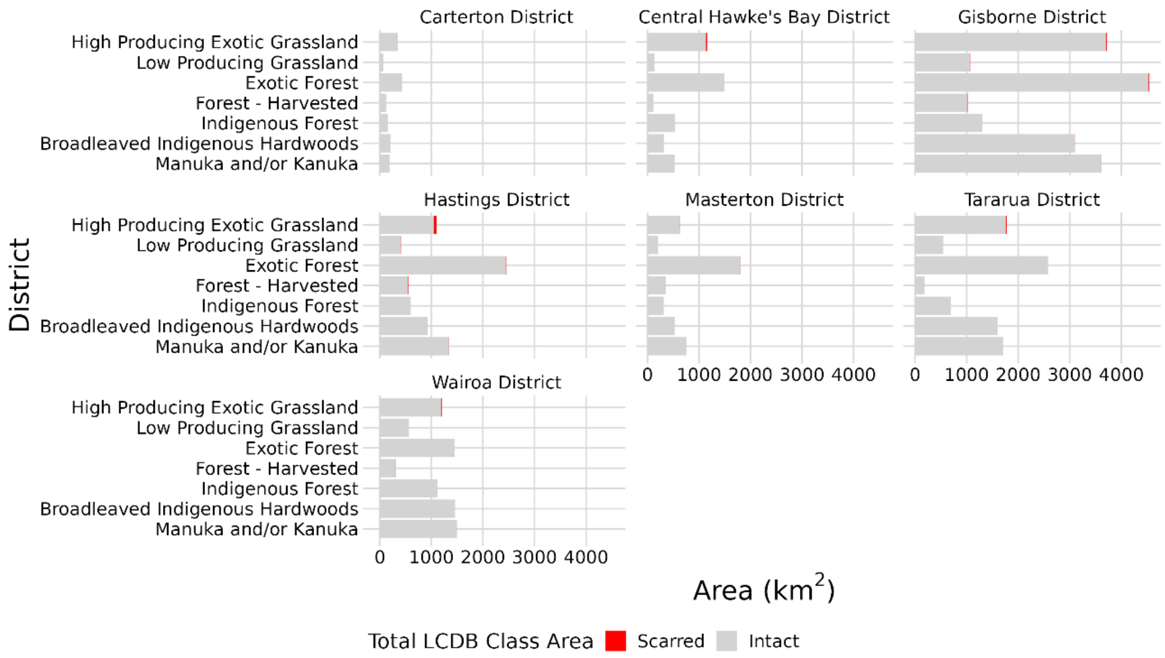

Figure A1. Total areas of different land-cover types on LUC Classes 6 & 7 land, by territorial authority.

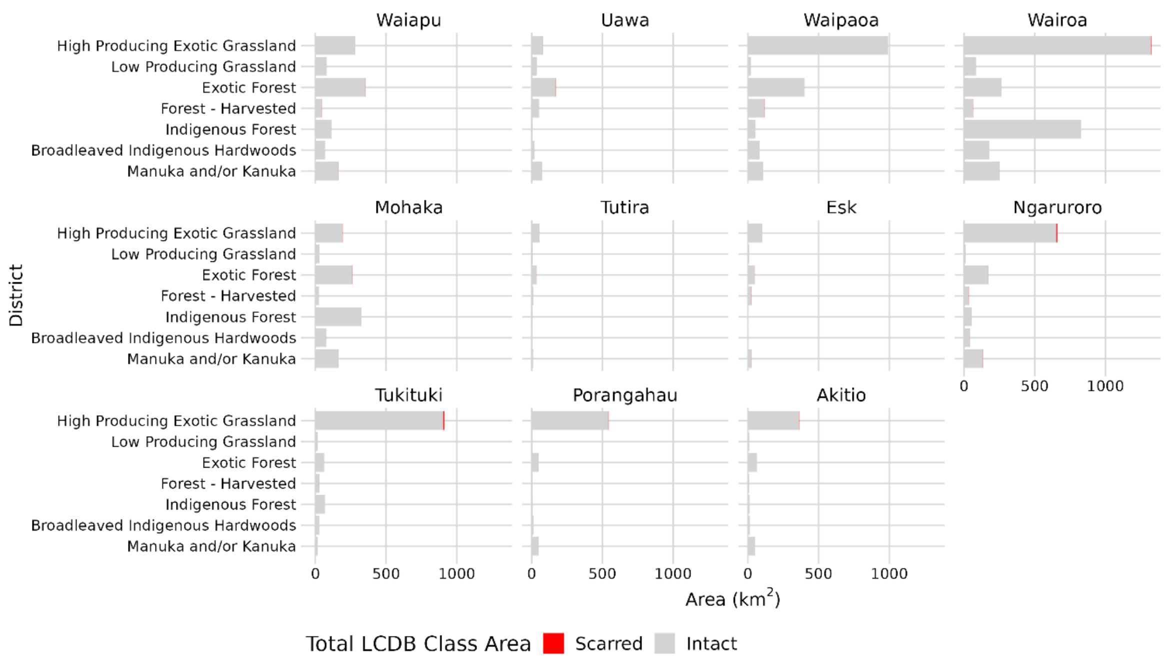

Figure A2. Total areas of different land-cover types on LUC Classes 6 & 7 land, by major sea-draining catchment.

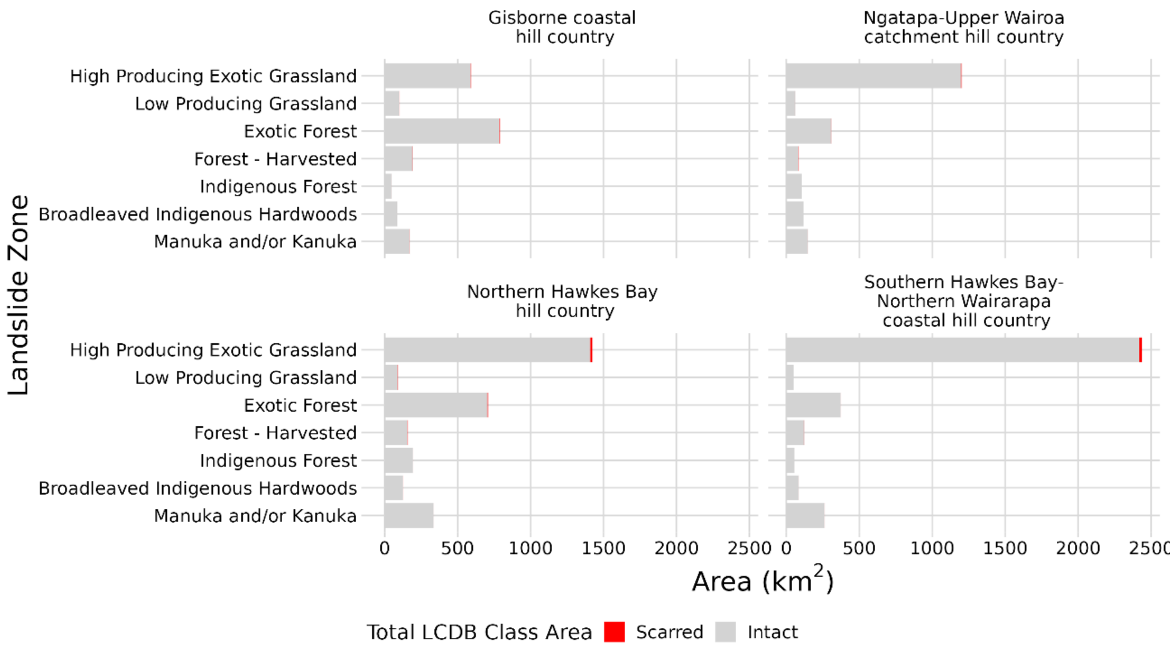

Figure A3. Total areas of different land-cover types on LUC Classes 6 & 7 land, by damage zone.

Appendix 2 – Erosion scars and Highly Erodible Land (HEL)

Table A-4. Area of landslide scars in different land covers, by territorial authority (km^2)

Landslide Zone	Erosion Risk	Total Area (km^2)		Area with erosion scars (km^2)		Proportion Scarred (%)	
		Woody	Non-Woody	Woody	Non-Woody	Woody	Non-Woody
Gisborne coastal hill country	Erosion risk	393	154	2.3	2.4	0.59	1.57
	Not at risk of erosion	852	643	1.7	2.8	0.20	0.44
Ngatapa-Upper Wairoa catchment hill country	Erosion risk	342	401	0.8	3.2	0.23	0.80
	Not at risk of erosion	430	900	0.6	2.5	0.13	0.27
Northern Hawkes Bay hill country	Erosion risk	460	244	4.9	7.9	1.07	3.24
	Not at risk of erosion	1050	1340	4.5	12.6	0.43	0.94
Southern Hawkes Bay-Northern Wairarapa coastal hill country	Erosion risk	220	188	0.3	4.3	0.14	2.28
	Not at risk of erosion	779	2278	0.7	14.2	0.09	0.62

Appendix 3 – Lithological factors affecting landsliding susceptibility

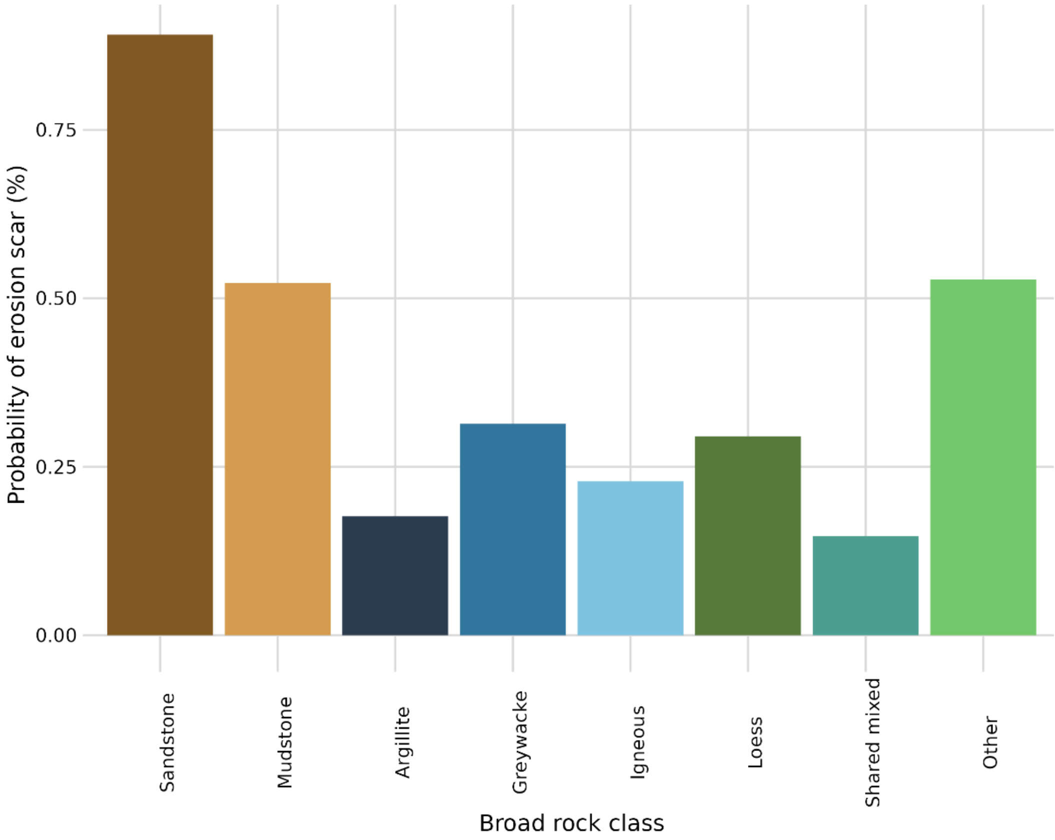

Figure A4. Landsliding probability on different broad rock classes across the entire study area. The area and classes were summarised from the NZLRI Layer "toprock" attribute. The "Other" category includes the code "Al" referring to "Alluvium, colluvium and glacial drift", which has a high erosion susceptibility. However, there is this category accounts for less than 1% of the total study area.

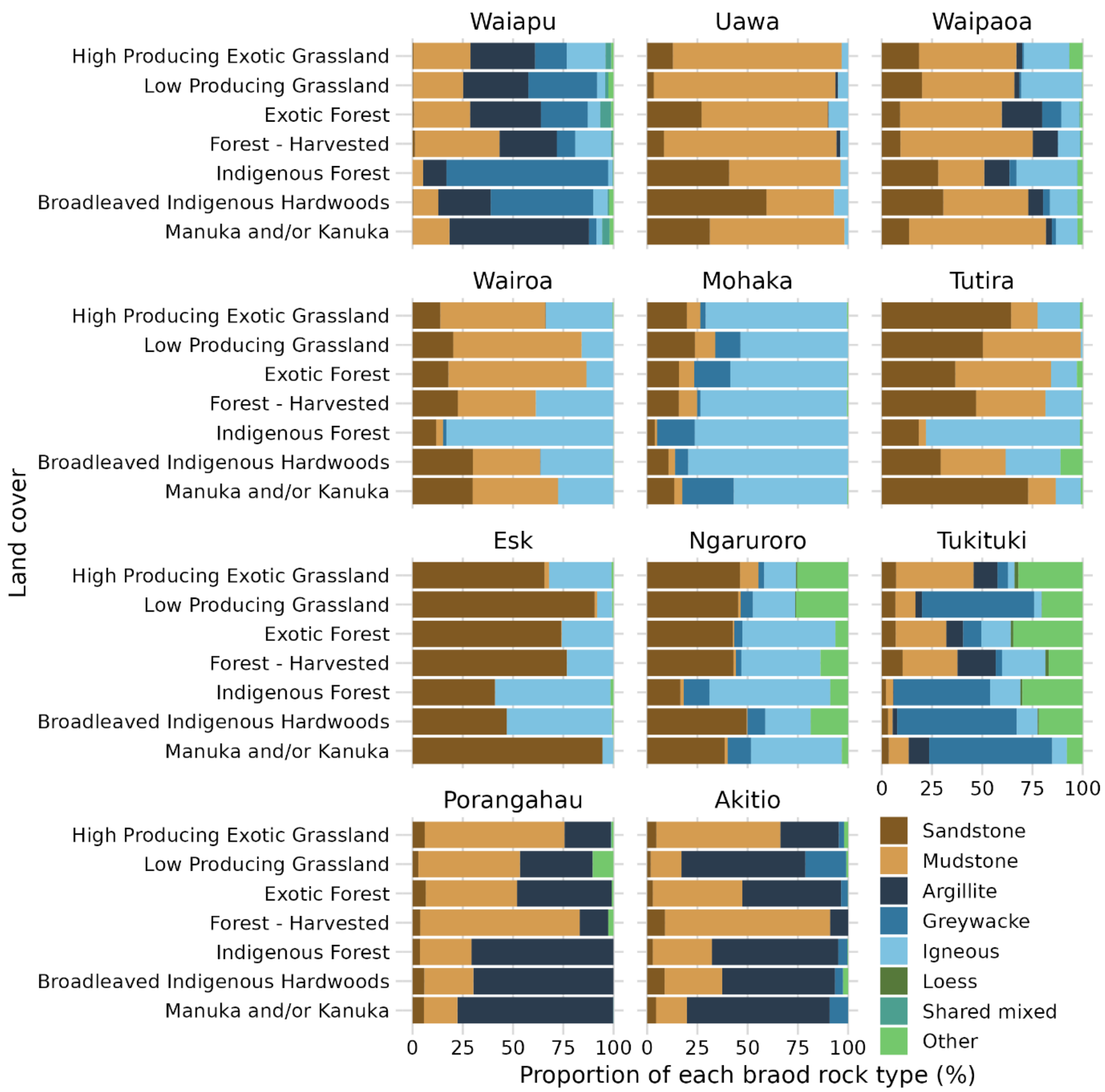

Figure A5. The proportions of different broad rock classes within each of the sea-draining catchment, disaggregated by land cover class.