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Shaping Landscapes – Landslide Analysis from Cyclone Gabrielle in Hawke's Bay, New Zealand

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Abstract

Cyclone Gabrielle severely impacted the Hawke's Bay region's natural capital to the extent that it would take many years to recover. Alongside its impacts on built capital, such as bridges, roads, homes and businesses, are the impacts on natural capital, including geology, soil, biodiversity, air and water. The focus of this work is on the impacts on soil and regolith in the form of landslides, which embed the surface geomorphic process dynamics of erosion to runout and deposition. Research has been undertaken by Hawke's Bay Regional Council (HBRC) to investigate the direct impacts of the cyclone on rural land stability in the region through geospatial analysis and the System Dynamics of landslides. Determinants of failure were assessed such as slope, aspect, antecedent weather, land use, land cover and the influence of any mitigation measures that promote resiliency. It is well documented that vegetation reduces erosion; with management plans stretching back beyond Cyclone Giselle and Bola. The question is, how have these land use changes measured up against the force of Cyclone Gabrielle? An initial farm-scale analysis found that the presence of trees at Awapapa Station in the Wairoa catchment likely influenced a reduction in slips by 67% when adjusting for farm size and slope. Once such information is known, the issue becomes managerial, where future planning to mitigate the impact of such events at the regional scale is critical. Here System Dynamics modelling is a useful tool to investigate how land use interventions can unfold over time and lead to positive outcomes for soil stability and economic output. This research provides a proof of concept of how System Dynamics can be employed to assess interventions ahead of time for rural areas.

Keywords: Cyclone Gabrielle, Erosion, Sedimentation, Land-use Planning.

Introduction

The impacts of Cyclone Gabrielle on the 13th and 14th of February 2023 in Hawke's Bay were broad, impacting the triple bottom line of economic, social, and environmental considerations. This research focuses on three elements of this disaster for rural communities: 1) the impacts on the natural capital of soil and regolith through the physical processes of sediment erosion and deposition. It explores some of the direct erosional and depositional impacts sustained through empirical measurements and observations by various agencies. 2) The influence of planting trees on pastoral hill country farms to reduce soil loss. It uses detailed geospatial analysis undertaken on two contrasting farms: Awapapa and Dumgoyne Stations. And 3) proposes a catchment management planning tool using System Dynamics in Vensim® simulation software to plan for and mitigate these adverse effects in the future [1, 2]. It takes a futures focus by investigating land use management and planning through modelling at the regional scale. Figure 1 illustrates two types of slips prevalent throughout the Hawke's Bay region and some resulting sedimentation of the floodplain.

Figure 1: Photo A shows some deep flows on a convex dome with little hydraulic head. Photo B illustrates a translational or planar slide perpendicular to the bedding plane. Photo C shows impacted vines in the Esk Valley smothered in sediment and woody debris.

Impacts on Natural Capital

The following section highlights some of the geomorphic research that was undertaken in Hawke's Bay directly after Cyclone Gabrielle. Many agencies rallied after the event to garner a better understanding of the extent of what had happened and what are some of the ramifications of such extreme storms from a scientific perspective. A selection of these are summarised below.

Manaaki Whenua Landcare Research (MWLR) undertook one of the first assessments after the event using GIS remote sensing on Sentinel 2 satellite imagery to produce the report 'Rapid Assessment of Land Damage – Cyclone Gabrielle' [3]. The report highlights that there were over 300,000 landslides along the East Coast, each typically comprising 1,000 tonnes of soil with a conservative economic cost of approximately NZ$1.5 billion. 61% of this damage occurred in Hawke's Bay and of that, 63% was in high-producing grassland and 13% occurred in exotic forests. One key finding is that woody vegetation reduced modelled landslide probability by 90%. Figure 2 illustrates the area of landslide scars in Hawkes Bay by landcover as reported by MWLR [3].

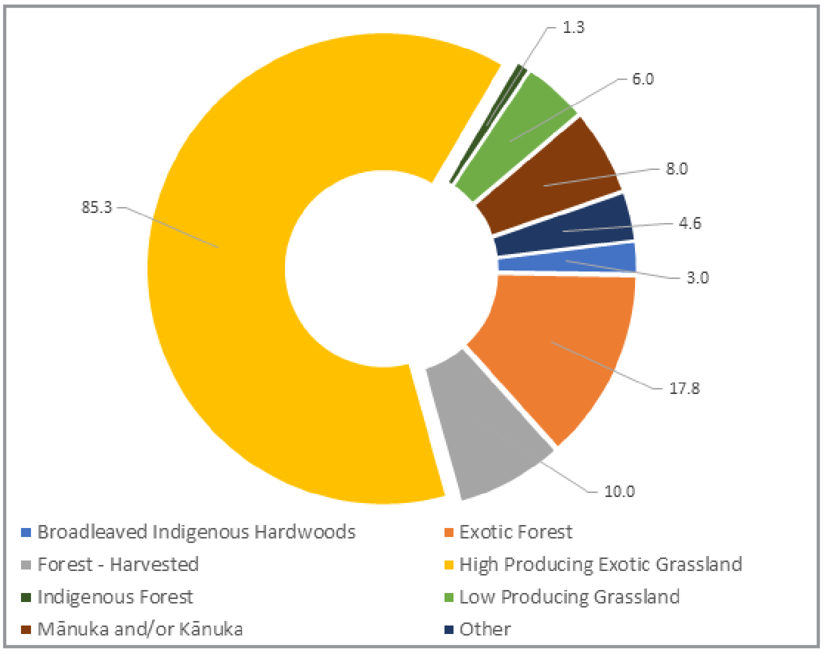

Figure 2: The Area of Landslide Scars (km^2) by Land Cover in Hawke's Bay Adapted from MWLR [3].

Concurrently, GNS undertook a landslide point and debris trail mapping exercise across impacted areas of the North Island [4]. This research relied on intensive manual digitising in GIS of the location of slips and the digitising of lines for the debris trail, or run out. The mapping showed a significant amount of pastoral farmland impacted compared to exotic forestry and native vegetation. However, the remote sensing approach will add bias as landslides under the canopy are hard to distinguish. Nonetheless, GNS has mapped over 85,000 landslide points and debris trails in Hawke's Bay to date. Figure 3 illustrates the intensity of the mapping and the slips in pastoral land in Hawke's Bay.

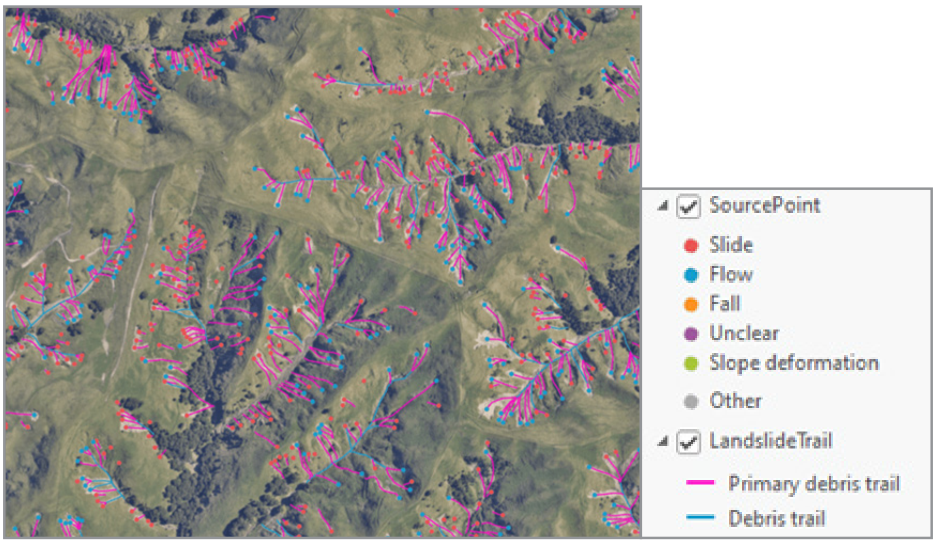

Figure 3: GNS Landslide Mapping of Slip Points and Debris Tails.

Stepping away from GIS into more classical sediment research, NIWA through the expert hand of Dr Arman Haddadchi undertook particle size distribution analysis in the Esk Valley. A task that required taking sediment cores around the floodplain for lab analysis (Figure 4). Dr Haddadchi found that the maximum deposition depth from cores was 300 cm. The predominant sediment particle size through the main catchment is very fine to fine sand. Whereas the predominant sediment particle size at Whirinaki is silt/clay. Thus, one could assume that the finer particles settled out in the low-energy environment around the Pan Pac Factory and Whirinaki Village.

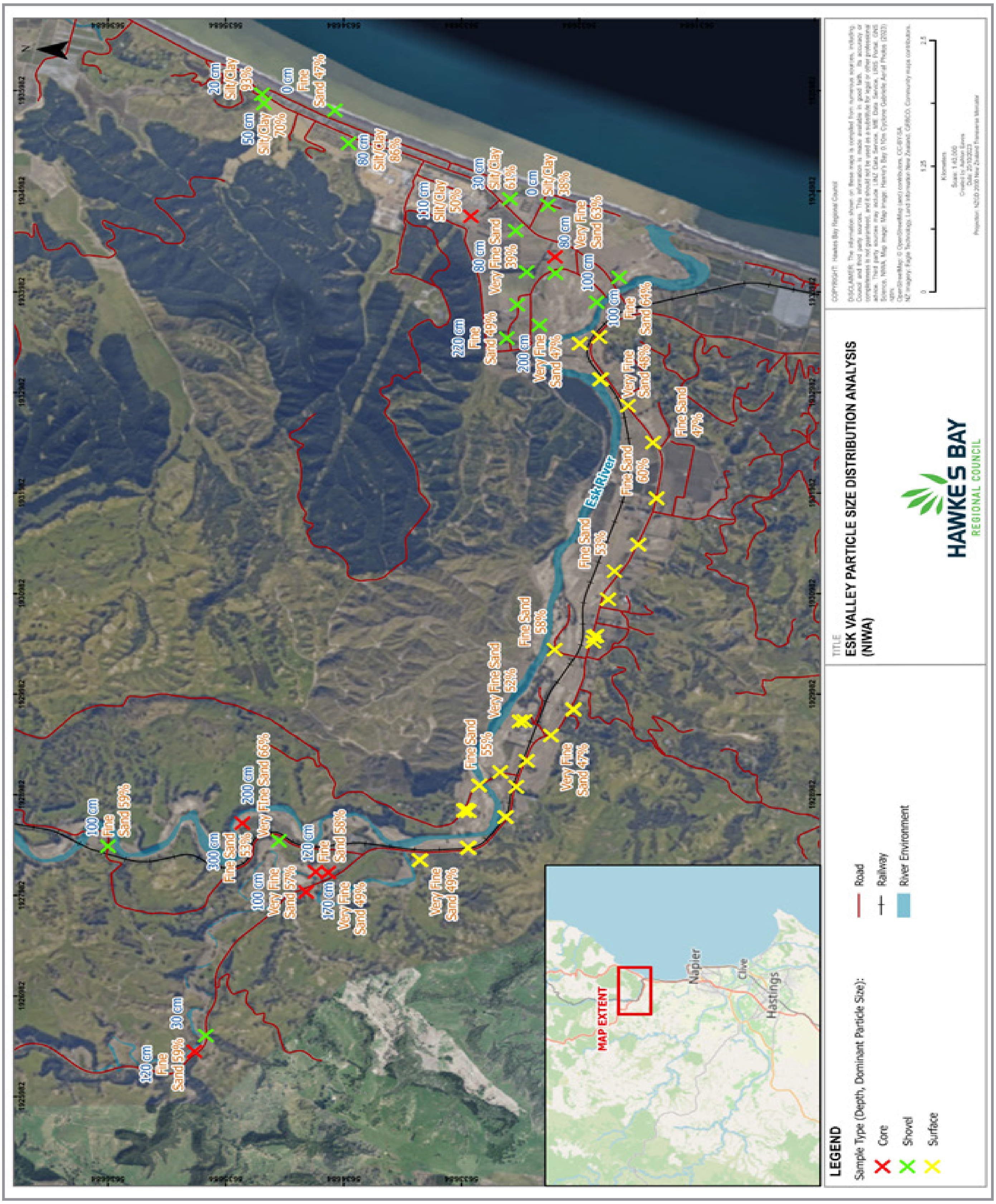

Figure 4: Locations, Depths, and Textures of NIWA's Esk Valley Particle Size Distribution Analysis.

One curiosity discovered by the author was the relocation of a semi-intact house in the Esk Valley. Comparing before and after imagery determined that the house was not previously located in the vines. As shown in Figure 5, the house travelled approximately 650 m downriver while avoiding many other buildings and remaining relatively well intact.

Figure 5: Photo A Shows the Relocated house. Photo B Shows the Original Location at the Top Left of the Image and where it Travelled to Approximately 650 m Downriver.

Farm-scale Analysis

Awapapa Station in the Hangaroa Catchment of northern Hawke's Bay and Gisborne has been extensively planted in poplars for the last four decades. The neighbouring Dumgoyne Station was acquired in more recent times and is predominantly absent of established trees. Currently, 30% of Awapapa Station is planted in various trees that are mainly space-planted poplars following Cyclone Bola and Giselle. Whereas planting at Dumgoyne got underway more recently after purchase and it has more undulating terrain. Cyclone Gabrielle and other recent storm events provided an opportunity for HBRC to assess the efficacy of poplars and other tree plantings in reducing the number of landslides, or erosion mitigation, on the two farms [5].

The analysis followed Cyclone Gabrielle and previous recent adverse weather events dating back to March 2022 where 1233 slips were mapped over 534 ha. This study compared the occurrence of landslips on these properties and analysed the impact of landcover, land use capability, soil type, slope, rainfall, aspect and vegetation on landslip areas and counts, or spatial frequency. It weighted and normalised slips to farm area and slope. Figure 6 shows indicative photos of the Awapapa and Dumgoyne Stations and Figure 7 shows a map of the farms.

Figure 6: Photo A, Plantations of redwoods, spaced poplars and pines on the ridgeline at Awapapa Station. Photo B, Dumgoyne Station with establishing poplars and a small establishment of native vegetation. Notice the tilled land in the foreground where the land was flooded and a new fence installed.

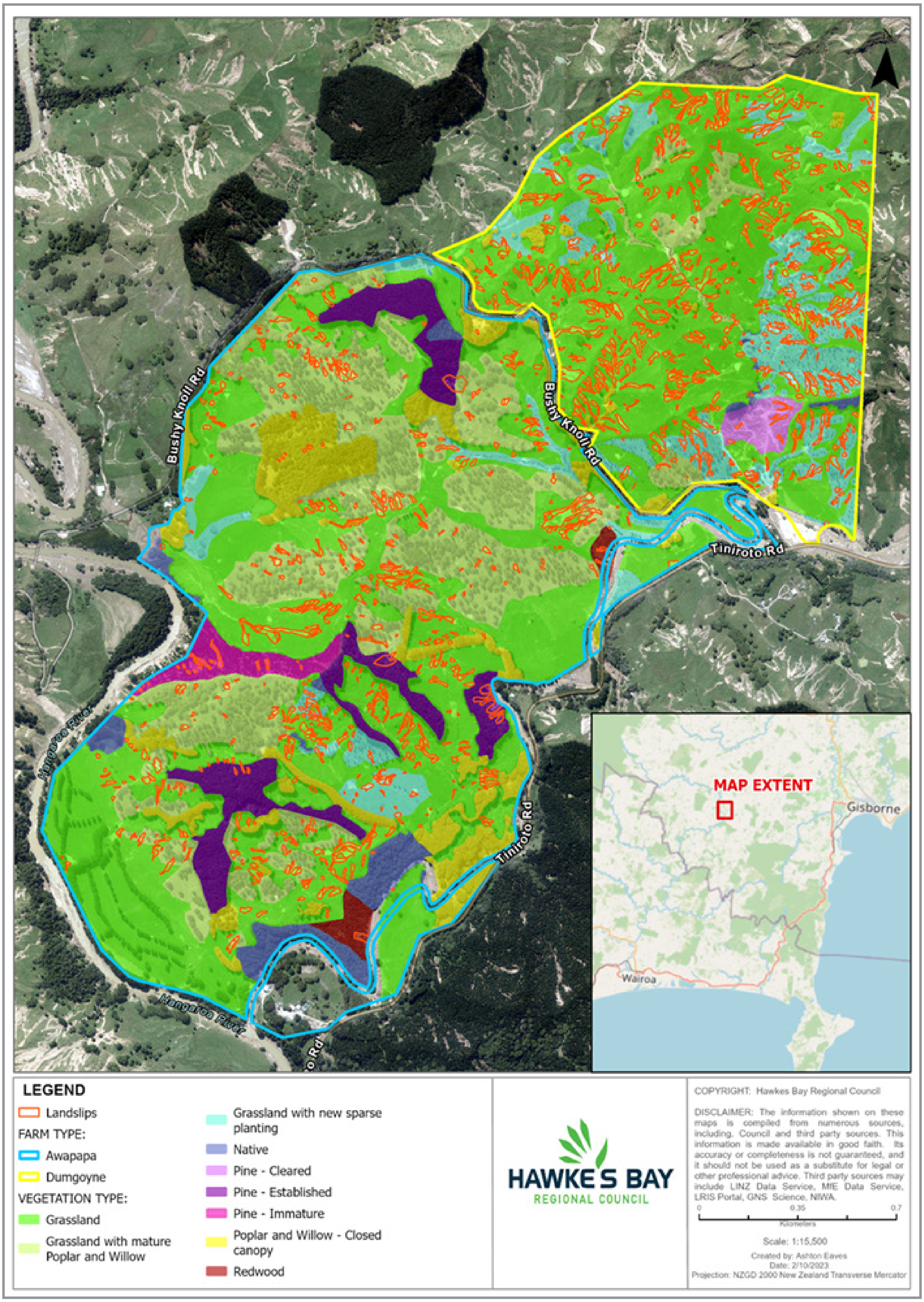

Figure 7: Map of Awapapa and Dumgoyne Stations Showing the Prevalence of Slips Alongside Land Cover.

The analysis found that the presence of trees on Awapapa Station likely influenced a reduction in slips by 67% when adjusting for farm size and slope. Adjusting for farm size alone, vegetation reduced slips by 45% across the two farms. Grassland is the least stable vegetation cover and is the dominant cover in which slips occurred on both properties. Figure 8 sums up the normalised proportion of landslide area by land cover with totals for each farm. The normalisation accounts for differing farm sizes and slope distributions.

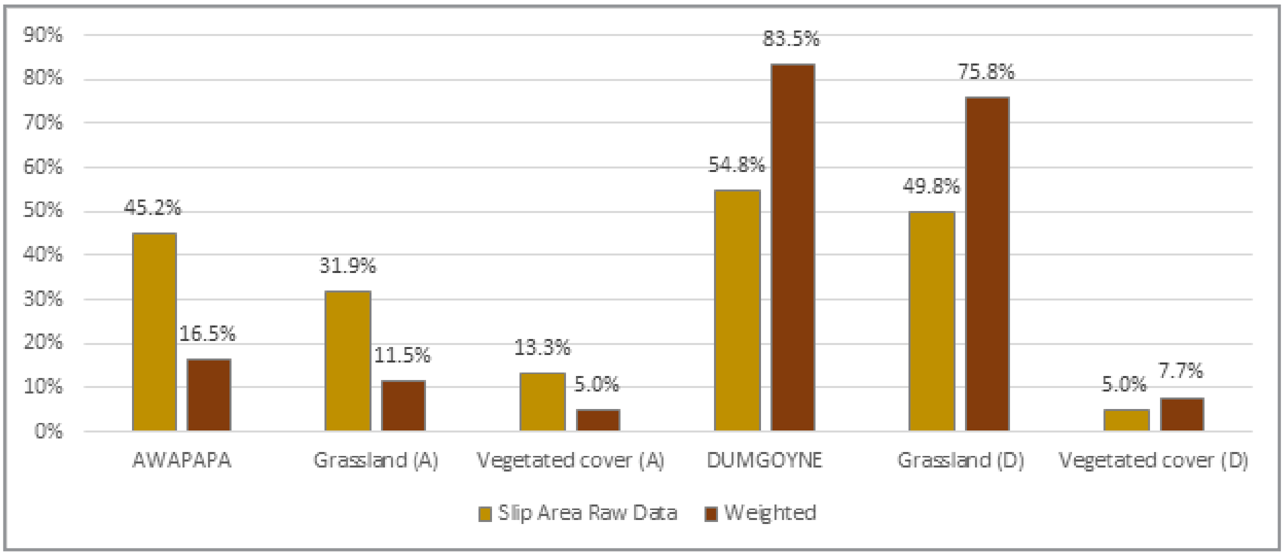

Figure 8: Normalised Landslide Area by Land Cover with Totals for Each Farm.

Figure 9 shows the number of slips per hectare by each farm. Notably, the rate of slips for Dumgoyne Station is 3.68 ha-1 whereas for Awapapa the rate is lower at 1.67 ha-1. Note that the areas in redwood, immature pine, cleared pine, Dumgoyne poplar and willow closed canopy and Dumgoyne native were not large enough to confidently conclude.

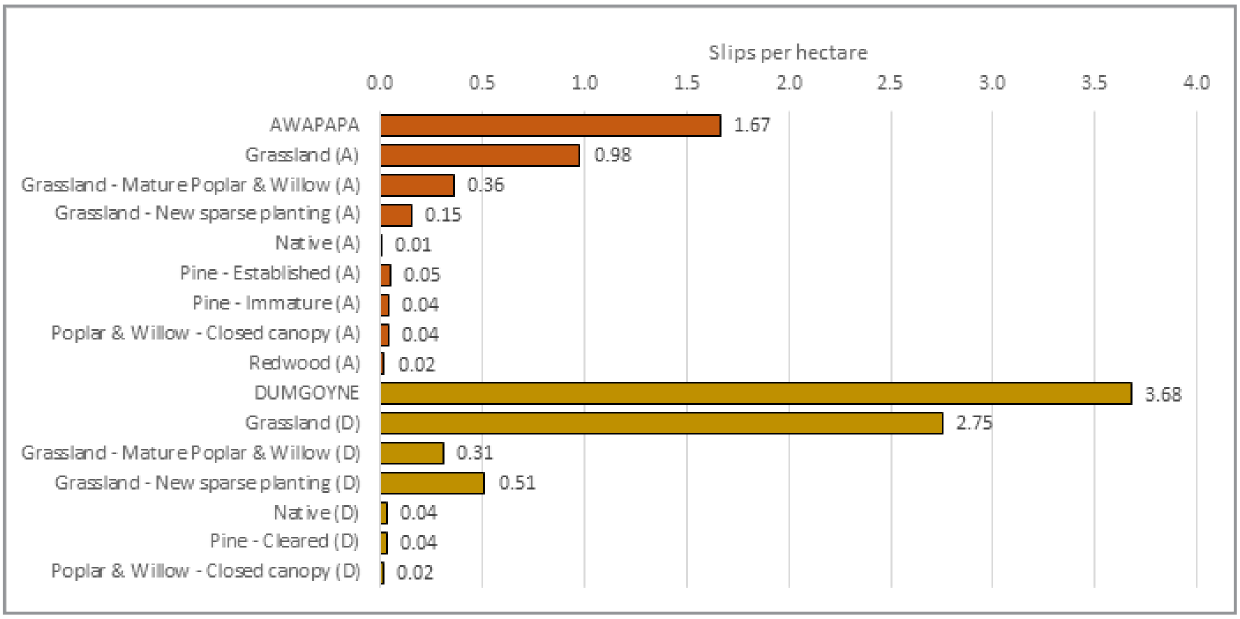

Figure 9: Slips Per Hectare Across the Two Stations Under the Varying Land Covers.

In addition to vegetation cover, the slope had a discernible influence on landslips alongside soil type, with rainfall just outside the bounds of statistical certainty. Therefore, as expected, slope is a critical contributing factor to landslips. Space-planting slopes above 20° in trees is effective in reducing the likelihood of erosion during severe weather events.

To justify this analysis, it is useful to visualise the slip density spatially. Kernel density estimation, a probability density function, was conducted to see whether the results correlate is visible in Figure 10.

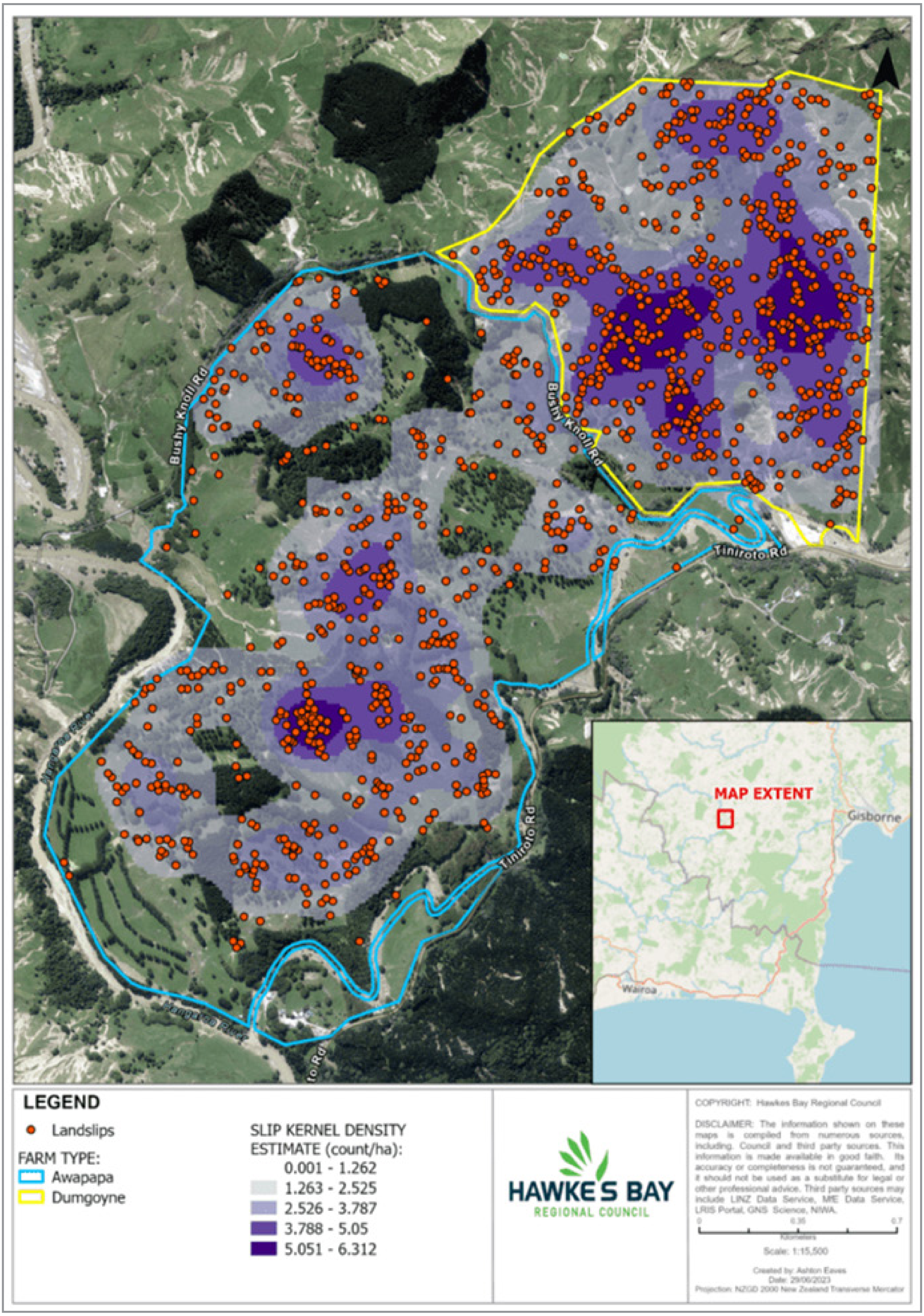

Figure 10: Kernel Density Estimates (or Probability Density Function) Across the Two Farms.

Land-use Management & Planning

Land-use management and planning move beyond the empirical and into the hypothetical through future scenarios modelling at the regional scale. It was borne out of an initial feasibility study as part of the Land For Life Programme [6]. The Programme promotes and supports the implementation of sustainable land-use practices for erosion reduction. Traditionally, implementations to reduce erosion have centred around the efficacy of space-planted poplars on pastoral slopes with high landslide susceptibility. An alternative to this has been plantation forestry. This research modelled these interventions over the long term to derive financial benefits and costs to industries associated with their implementation and quantify anticipated reductions in erosion and sedimentation. It illustrates indicative findings from the modelled scenarios and model development is ongoing from this proof of concept.

The method utilised two main processes with some sub-processes to ingest spatial analysis into hypothetical futures modelling at the regional scale. The first process was a geospatial analysis to discover the quantity of land in pastoral farming, and the quantity of that land susceptible to landslides. This process also included the development of treatment areas for scenario implementation. The second process used System Dynamics to model future scenarios from 2000 through to 2070. This timeframe allows for calibration with real-world data and gives ample time for the full benefits of any implementation to be realised. The scenarios are as follows:

- Baseline – Do nothing. Slips degrade natural capital leading to economic loss.
- Poplar poles intervention – Introduce space-planted poplar poles on land with a probability of 80 to 95% landslide susceptibility in 2024. Areas with a landslide susceptibility probability greater than 95% are retired for indigenous vegetation.
- Exotic forest intervention – Introduce exotic forests on land with a probability of 80 to 95% landslide susceptibility in 2024. Areas with a landslide susceptibility probability greater than 95% are retired for indigenous vegetation.

Here are the steps involved:

1. Define landslide susceptibility from LiDAR-derived map [7] (Figure 11).
2. Define slip-prone land (80 – 95% landslide susceptibility) and treatment areas (intersecting 0.25 ha grid). Figure 12 illustrates these layers zoomed in to Ruakituri. The model set up for this analysis uses the blue treatment areas.
3. Build a stochastic system model to execute scenarios in Vensim® [2]. Figure 13 shows the graphic user interface of the stock-flow model with the integrated submodules.
4. Calibrate the model to real-world data for the period 2000 – 2020 then simulate divergent future scenarios to 2070.

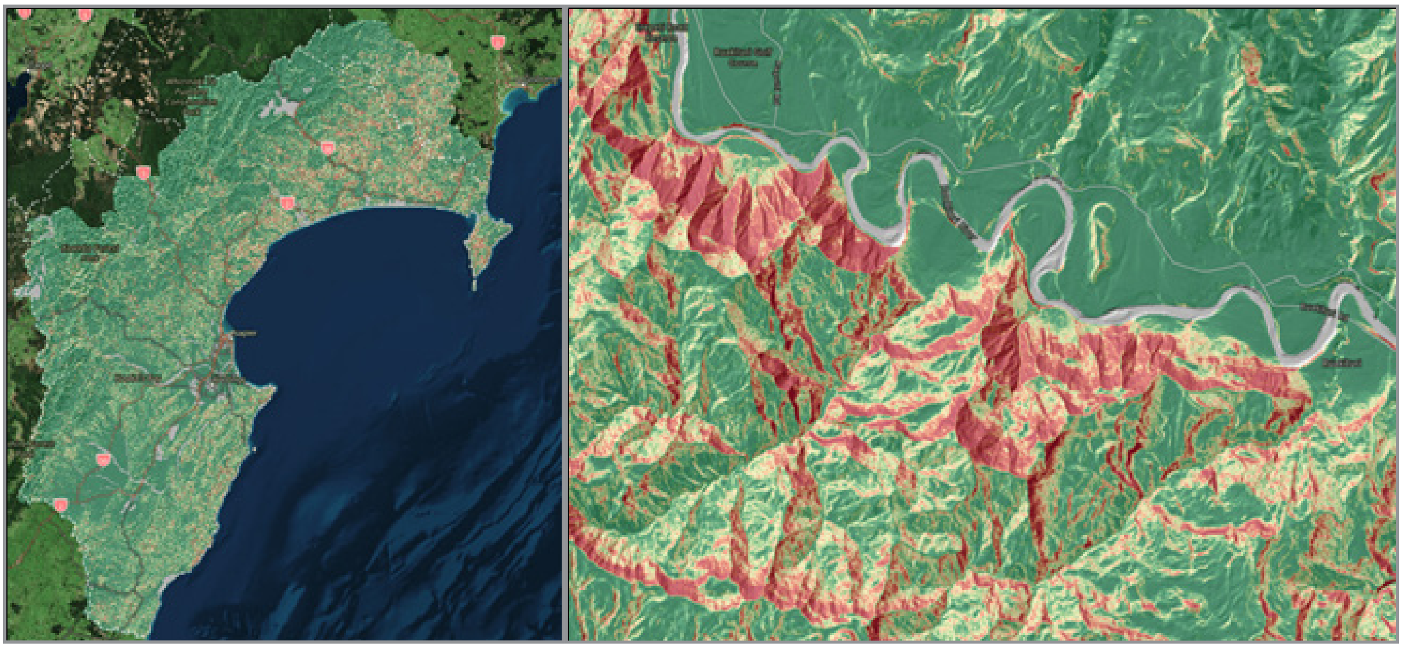

Figure 11: 2020 Lidar Defined Landslide Susceptibility Probability Developed by MWLR. The Layer is at the Regional Scale with a Zoomed-in Portion to Illustrate its Detail.

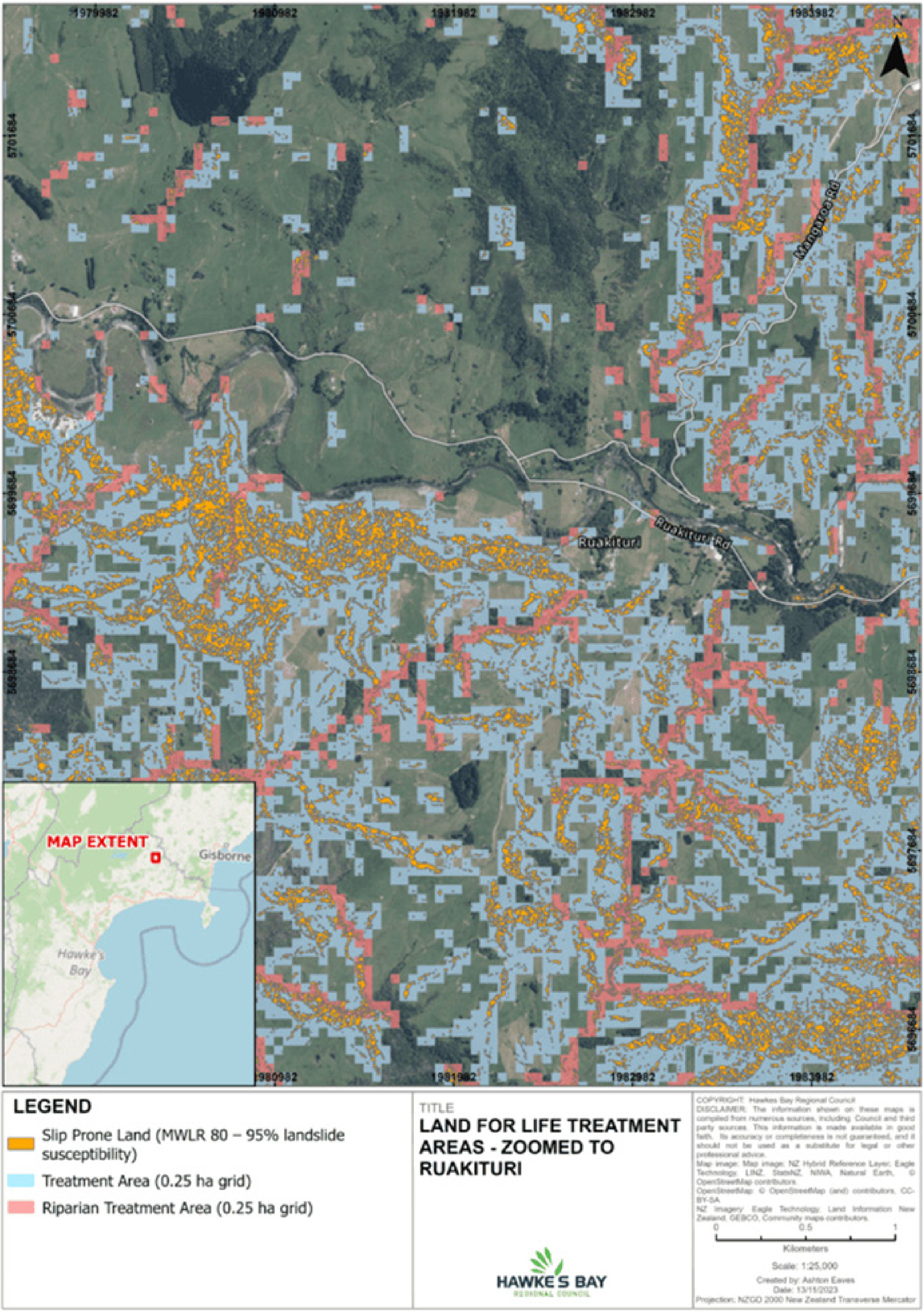

Figure 12: Slip-Prone Land and Treatment Areas Zoomed to Ruakituri.

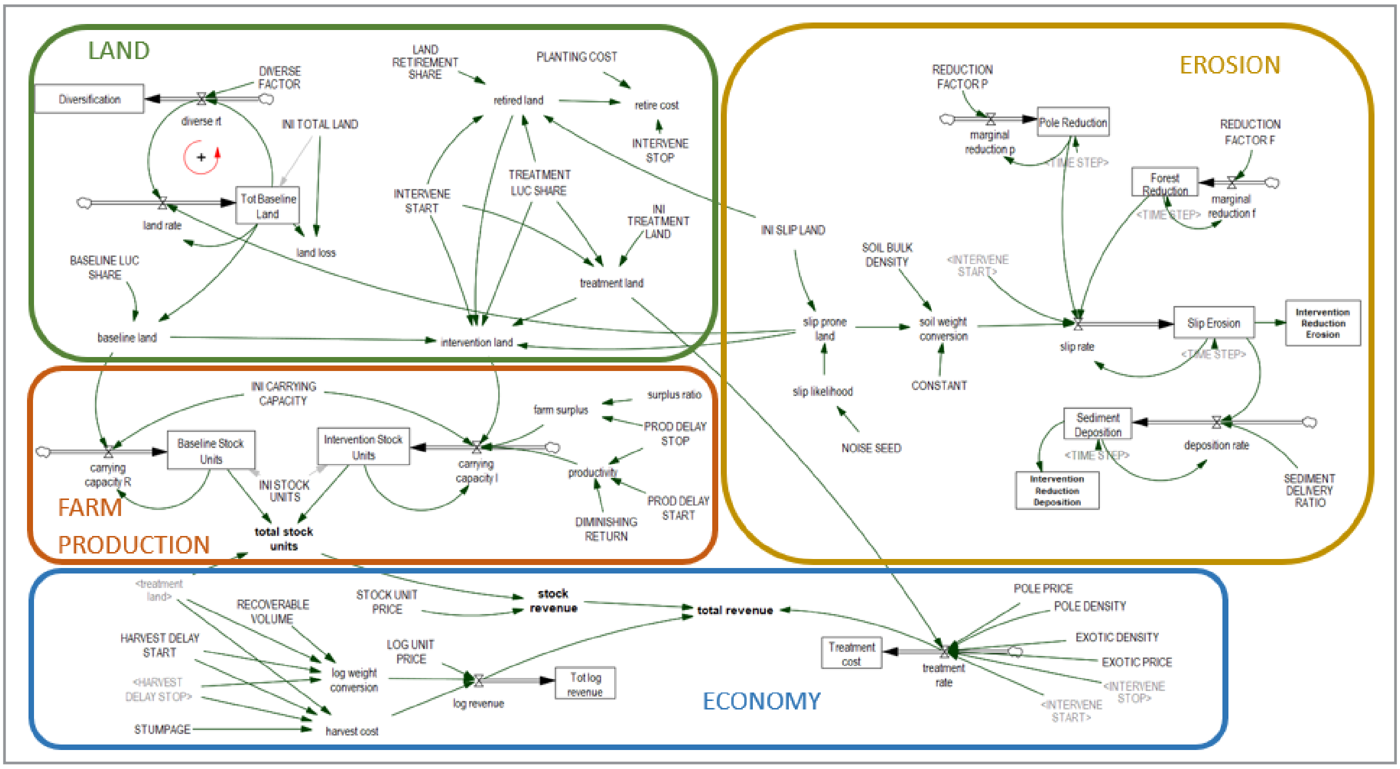

Figure 13: The Vensim® stock-flow model for testing scenarios from 2000 to 2070. The land sub-module processes the change in land for pastoral farming in hectares. The erosion sub-module derives changes to erosion and sedimentation given stochastic slips under the various scenarios. The farm production sub-module takes the changing amount of land and applies differing carrying capacities. Finally, the economic sub-module sums costs and revenue streams.

The following results and brief discussion highlight the two main areas of investigation: 1) the change in erosion and sedimentation, and 2) the anticipated change in total farm revenue across the region.

Figure 14 shows the three scenarios over time against the backdrop of stochastic storm events triggering erosion over time. The interventions of planting poplar poles and exotic forestry on marginal land take place in 2024 leading to divergent scenarios by 2030. The baseline scenario continues with the same erosion rate while both interventions reduce landslide erosion beyond 2035. Exotic forests have an increase in erosion as harvests come online.

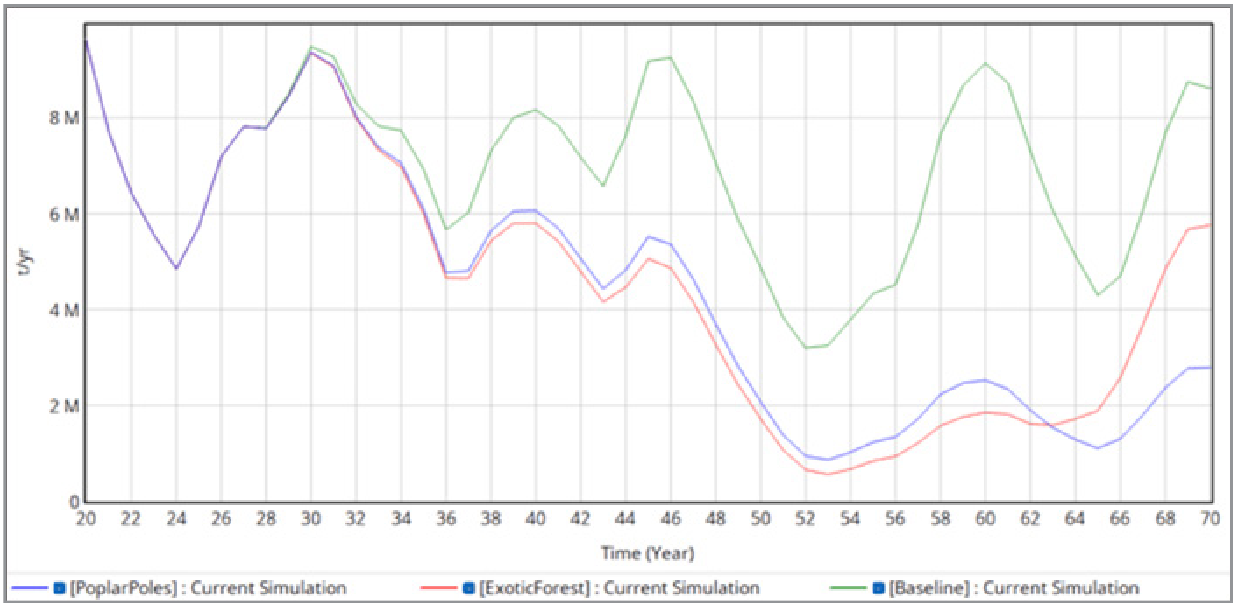

Figure 14: Indicative Slip Erosion Under the Three Scenarios in Tonnes Per Year.

To derive the benefit from an intervention, Figure 15 illustrates the percentage change against the baseline. By the end of the period, exotic forestry reduces erosion by 68% whereas poplar poles reduce erosion by 57%. These results are similar to the broadscale analysis undertaken by MWLR following the landslide impacts of Cyclone Gabrielle [3].

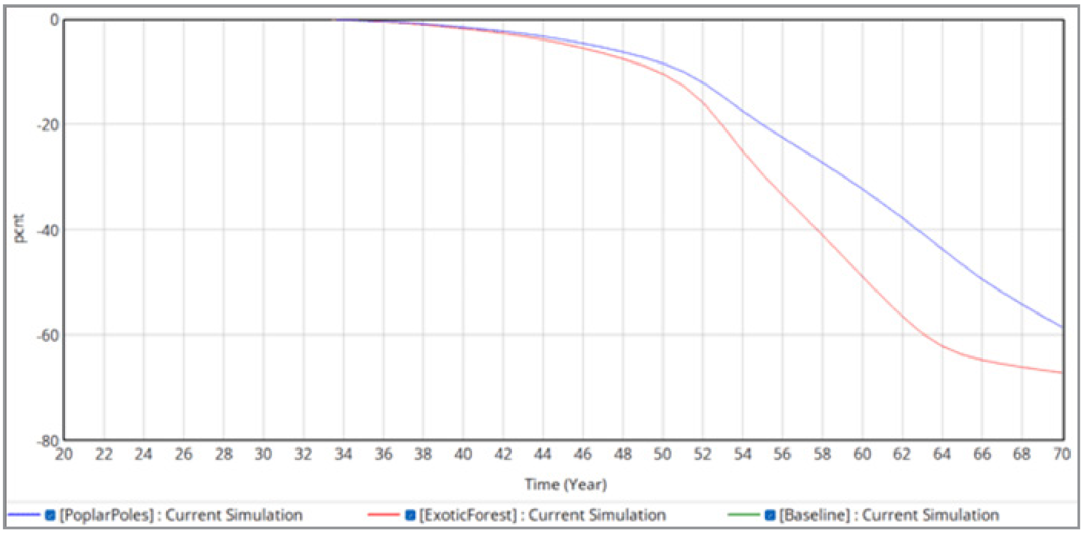

Figure 15: Indicative Change in Erosion under the Three Scenarios as a Percentage. Note that the Baseline is Zero.

The amount of sediment deposition from catchments is represented in Figure 16. Interventions reduce sedimentation compared to the baseline as expected. The model output for sedimentation does not match that of the HBRC State of the Environment report where regionally, landslide is the predominant cause of erosion, transporting about 5 million tonnes of fine sediment into waterways each year [8]. Therefore, more investigation is needed into this variable and the proportion derived from pastoral farming versus other land uses. Given that sedimentation is a proportion of erosion in the model, the trends are the same but the values differ over the period.

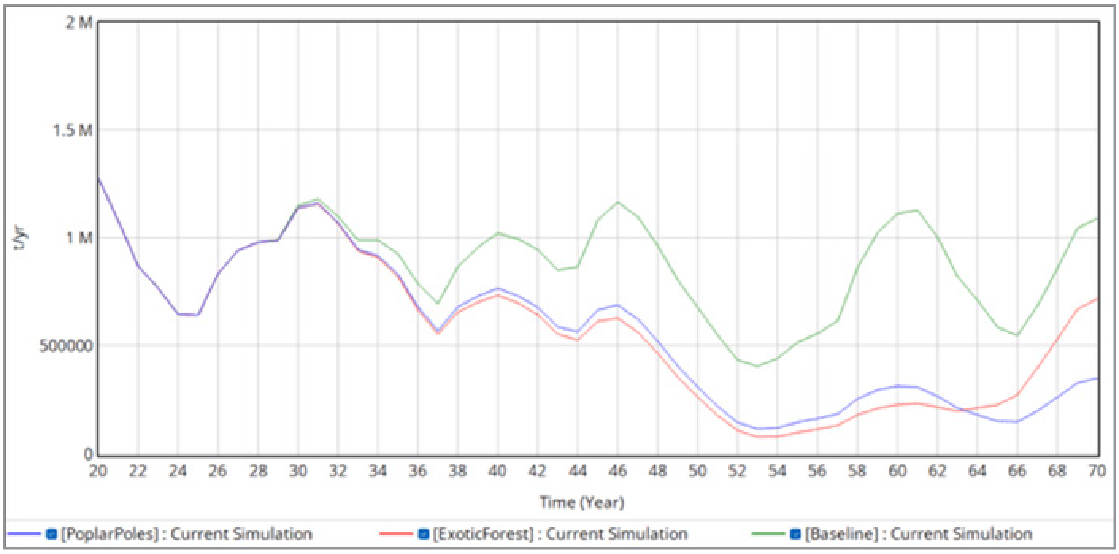

Figure 16: Indicative Change in Sedimentation under the Three Scenarios in Tonnes Per Year.

Figure 17 highlights changes to total revenue from pastoral land at the regional scale. Under the poplar poles intervention, total revenue dips below the alternative scenarios as trees are established and the carrying capacity of the land is reduced. As trees grow, total revenue surpasses the baseline in 2045 culminating with a significant increase in revenue over the baseline by the end of the period. Under the exotic forest intervention, after the significant drop in returns after planting (2024 – 2034), the total revenue stagnates below the other two scenarios until 2057 where it significantly increases above the other two scenarios as harvesting comes online. Total revenue falls slightly under baseline conditions and by the end of the period, farmers are worse off than the intervention scenarios.

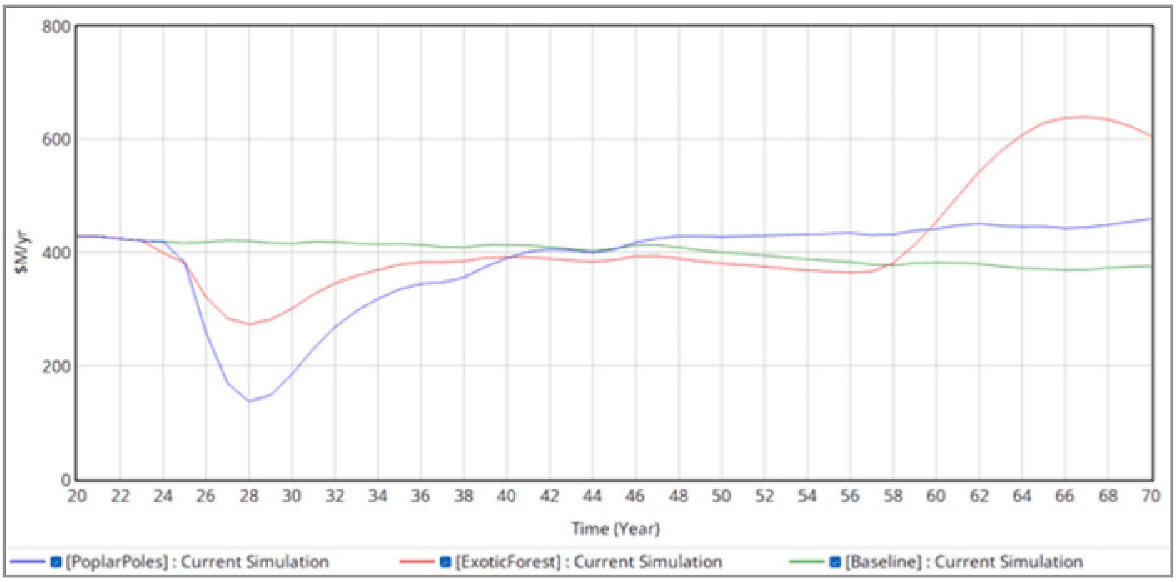

Figure 17: Indicative Nominal Total Revenue Under the Three Scenarios in NZ$ Million Per Year.

Overall, the scenario that performs best over the period is exotic forestry. However, this is due to its capacity to reduce slips more than what can be achieved through the space-planting of poplars and revenue generated from logs is currently higher than that of livestock units. Although post-harvest land vulnerability to slips is an issue. Fleshing out the future scenarios further might change this outcome if space-planted vegetation (either exotic or native species) could achieve reductions similar to or better than exotic forestry. Similarly, given flat wool prices, wool production is currently exempt from the modelling. Under more favourable wool prices, the outcome for total revenue could be more favourable for the poplar poles scenario, a consideration worth exploring. Similarly, movements of financial capital need to be incorporated into the model.

Concluding Remarks

Cyclone Gabrielle has had devastating impacts on the natural capital of soil which has indirectly impacted rural economies. However, cyclones are nothing new to the region and communities should anticipate future adverse events. Therefore, lessons learned today should create opportunities to install system resiliency tomorrow. New Zealand was unfortunate to experience such an event, but fortunate that it has the scientific and technical expertise to rigorously analyse such events for causal relationships to better prepare future generations.

Regarding farm plantings in the farm-scale analysis, more scientific research is needed at the species level for more targeted treatments and increased biodiversity gains where exotics can be supplemented with indigenous varieties. This could include a geospatial analysis of areas that currently exist with alternative species and how they performed throughout the event.

Concerning modelling future scenarios, the current model requires more economic inputs on these rural industries and their dependencies. The model also requires more dynamic feedback to account for national and international commodity prices and other market drivers given the long timeframes involved. Such models help with long-term land use planning as economic drivers shift and uncertainty creeps in. Nonetheless, models are only useful if their outputs lead to action. Therefore, future scenarios will need buy-in from communities and stakeholders to intervene in the system.

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