TŪĪ TO ŌTAUTAHI

An investigation of native replanting as a technique to increase tūī population and dispersal across Banks Peninsula, New Zealand.

"Tiakina nga manu, ka ora te ngahere. Ka ora te ngahere, ka ora nga manu"

"Look after the birds and the forest flourishes. If the forest flourishes, the birds flourish."

-Matauranga o Ngahere (Manaaki Whenua / Landcare Research, n.d.)

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CHRISTCHURCH NEW ZEALAND

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Executive Summary

Tūī (Prosthemadera novaeseelandiae) are an endemic New Zealand songbird that effectively disappeared from Horomaka/Banks Peninsula and Ōtautahi/Christchurch last century, as colonisation led to increased deforestation and predation. However, recent efforts have seen tūī translocated to Hinewai Reserve, and the Christchurch Foundation aims to bring them back to Ōtautahi/Christchurch by developing a habitat corridor. This project aims to inform their actions by answering the following research question: "Where can native species best be planted to enhance the existing tūī corridor between Hinewai Reserve and Ōtautahi/Christchurch, encouraging tūī populations to expand into the city?" Several methodological approaches were employed: we collated expert opinions, reviewed relevant literature, and used the findings to inform GIS (Geographical Information Systems) analysis. Modelling demonstrated that Horomaka/Banks Peninsula has high connectivity between patches of ideal habitat. The connectivity model was assessed against terrain and climatic characteristics to identify optimal native planting sites. We conclude that the leading priority to increase tūī dispersal across Banks Peninsula towards Christchurch is to increase population through expanding predator control and diverse planting of tūī food species. Secondary priorities include increasing habitat patch size, composition, and cumulative area, which we suggest can be most effective when informed by our planting suitability map. Study limitations included literature and data scarcity, and constraints in time and expertise. Further research is required on tūī habitat and autumn/winter food species availability in Ōtautahi/Christchurch, and also strategies to increase predator control efficacy across Banks Peninsula.

1. Introduction

Horomaka/Banks Peninsula (hereafter Horomaka), situated on the east coast of New Zealand's South Island, extends southeast from Ōtautahi/Christchurch (hereafter Ōtautahi), comprising 1200 km2 of convoluted hillsides. Prior to the arrival of Europeans, around half (an estimated 566 km2) of Horomaka was covered in podocarp-dominated forest, including lesser amounts of broadleaved and coniferous hardwoods (Boffa Miskell, 2007; Harding, 2003). However, the area's colonisation from 1840 rapidly decreased biodiversity across the peninsula (Boffa Miskell, 2007; DOC, 2021; Harding, 2003). By 1900, only 0.6 km2 of the original forest remained, and today, remnants are small and fragmented (Harding, 2003).

Among species affected by land clearance was tūī (*Prosthemadera novaeseelandiae*), an endemic honeyeater that underwent local extinctions in Ōtautahi and across Horomaka between 1970-1990, due to factors such as habitat loss and predation (ECAN, 2010). Habitat loss is a reduction of total habitat area and fragmentation of that area into smaller patches. It is widely recognised as a global and national threat to biodiversity (Bennett, 1987. Heaphy, 2021; Henle et al., 2004; Tscharntke et al., 2012). Furthermore, anthropogenic processes have accelerated habitat loss, with many species failing to adjust (Hilty et al., 2006). Consequently, they disperse from the area or are subject to high mortality and extinction rates (Rybicki & Hanski, 2013).

Efforts have been made to re-establish tūī across Horomaka, beginning with the translocation of 72 adults to Hinewai reserve in 2009/2010. However, expert opinion and iNaturalist tūī sighting data (iNaturalist contributors, 2022) suggest that this population has been slow to expand, and that further efforts are required for sustainable tūī presence in Ōtautahi. Ecologists consulted agreed that future efforts need to include increasing the extent and quality of habitat. The Christchurch Foundation (TCF), in collaboration with Meridian Energy, have committed to further work on this aspect of tūī restoration. They have achieved a high amount of planting through their efforts, but these have been spatially opportunistic. TCF has requested research to inform a more targeted approach to site selection for forest restoration, increasing the efficacy of these projects in bringing tūī back to Ōtautahi.

There are many ways in which native plantings and tūī restoration can bring environmental and social benefits. Biocentric worldviews see that all species, including tūī and native plants, hold inherent worth. For example, tūī has ecosystem value as a seed disperser (Castro & Robertson, 1997). Humans will also experience benefits from increased planting, as a significant relationship between natural green space and mental well-being exists (Houlden et al., 2021). Such projects also absorb carbon emissions, mitigating climate change (Di Sacco et al., 2021). The reintroduction of native biodiversity within New Zealand at Wellington's Zealandia Wildlife Sanctuary has positively impacted the natural environment, and the well-being of the city and its inhabitants (Marques et al., 2019). Spokespersons for Te Hapū o Ngāti Wheke have expressed that a priority for their hapū is to protect and enhance native species and forest and that to bring tūī back to their Tākiwa "would be a dream" (John Kottier, personal communication, 20 September 2022).

Much of the soil within the Horomaka consists of highly fertile loess, making the area ideal for reforestation projects (Wilson, 1993). In addition, the southern face of the Peninsula produces higher precipitation compared to the northern face due to orographic precipitation from moist southerly airflows (Sturman, 1986). When selecting species for reforestation, consideration of the interrelationship between tūī and environmental factors is vital, ensuring that habitat and food requirements are met. Specifically, studies into habitat suitability for birds have identified the importance of having a mixed composition of vegetational species and a wide variety of food (Dong et al., 2003; Purify et al., 2019).

Essential concepts in conservation biology are fragmentation, habitat division, and connectivity, which describe the mobility of tūī sub-populations across fragmented habitats (Fahrig, 2003). Connectivity can be achieved through wildlife corridors, which increase species resilience by facilitating genetic diversity, and flexibility to disperse when environmental conditions change (Hilty et al., 2007). Corridors can be either linear or discrete "patches" that facilitate the movement of biota between core habitat areas (the areas they can breed and flourish within) across a matrix of surrounding unsuitable habitats (Meurk & Hall, 2006). Corridors will help reduce the detrimental effects of habitat loss by aiding in restoring biodiversity across Horomaka and Ōtautahi (Heaphy, 2021). However, correct forest restoration planning is required to maximise the benefits of reforestation and connectivity, as outlined in the study by Di Sacco et al. (2021). Notably, the study states that people must work collaboratively to protect existing forests and focus conservation efforts on areas and species that will maximise biodiversity.

To address tūī habitat connectivity concerning the goals of TCF, we aim to answer the research question: "Where can native species best be planted to enhance the existing tūī corridor between Hinewai Reserve and Ōtautahi/Christchurch, encouraging tūī populations to expand into the city?". We will investigate and develop a map of the best areas to plant native species to see tūī established in Ōtautahi / Christchurch, with a focus on tūī habitat and food requirements. We are using the following objectives to inform this:

1.1 Objectives

I. Employ a mixed methods approach to establish what limits sustainable Tūī population growth and dispersal from Hinewai to Christchurch.

II. Map existing tūī movement corridors on Horomaka through GIS methods.

III. Categorise the influence of terrain and climatic factors on native planting across Horomaka within GIS.

IV. Combine these results in GIS to derive a site suitability analysis for native planting, highlighting planting sites with the greatest potential to increase sustainable tūī dispersal from Hinewai to Christchurch, and facilitate establishment of satellite populations.

V. Make broad recommendations on best measures for future native planting efforts. to increase sustainable tūī population growth and dispersal across the peninsula.

2. Methods

We employed a mixed methodology approach (objective I) to increase scope and accuracy of conclusions (objective V). A literature review was conducted, which ensured a broad knowledge base, however there was a shortage of literature on Horomaka botany, and a severe shortage of relevant tūī literature. Gaps in literature were therefore filled by interviewing ecologists. The literature review also informed suitable approaches and tools for our geospatial analysis and highlighted important factors to analyse. Geospatial analysis was then performed using GIS software, leveraging findings from the prior two methods to address objectives II – IV,

2.1 Literature Review

Knowledge acquisition began with review of scientific literature across five areas:

- The physical environment
- Anthropogenic history
- Biological aspects of site suitability
- Habitat fragmentation, connectivity & corridors
- Social, economic and environmental benefits

2.2 Expert Opinion

The literature gaps highlighted a need for more specific ecological details around tūī requirements, tūī movement, and local native planting requirements. We approached many ecologists, of whom four were willing to take the time to inform our research. We used semi-structured interviews (two in person and two via email). We asked directed questions about tūī, flora, or both, depending on the expert's speciality (Table 1). This expert input from ecologists was crucial to this study. We also sought to incorporate Mātauranga Māori, another insightful form of expertise; enough Mātauranga was shared with us to validate our research aim, but not enough for analysis.

Table 1: Table showing the ecologists interviewed for expert opinion, with their respective areas of expertise.

Qualification	Name	Tūī Authority	Botany Authority	Native Restoration Authority	Ōtautahi / Horomaka Expertise
Doctorate	Molles, L.	Y			Y
Doctorate	Meurk, C.		Y	Y	Y
Masters of Science	Innis, J.	Y			
Doctorate	Morris, J.		Y	Y	Y

2.3 GIS Analysis

2.3.1 Data Acquisition

We downloaded data for tūī sightings, landcover, annual precipitation, elevation, and NZ roads. Tūī sightings from iNaturalist (iNaturalist contributors, 2022). Landcover, and annual precipitation (Leathwick et al., 2002) data layers from Landcare Research's LRIS portal (LRIS, 2022). An 8m digital elevation model (DEM) from the year 2012, and NZ road data, from Land Information New Zealand (LINZ, 2022). All raster datasets, and subsequent analysis outputs, have a spatial resolution of $100m^2$ per pixel, spatially referenced in NZGD2000. GIS analysis using these datasets was completed in ArcGIS ArcMap (ArcMap, 2022).

2.3.2 Tūī Corridor Mapping

Understanding wildlife's need for connected habitat networks is rising along with the urgency of applying this knowledge, as increasing anthropogenic activity increases pressure to biotic populations and communities worldwide (Fahrig, 2003). The formative work in this field was The

Theory of Island Biogeography by MacArthur and Wilson (1967). The concepts defined were then developed over time, producing the popular Metapopulation Theory (Levin, 1970, as referenced by Hilty et al., 2006). Our study considered specific concepts established in this work (e.g., source-sink population dynamics). For our purposes, the literature review indicated that spatial modelling of connectivity and wildlife corridors would help identify optimal planting sites (either to improve existing corridors or to remedy corridor gaps). In addition, linkage Mapper (McRae et al., 2012) is an accepted modelling tool of only moderate complexity, therefore suiting our needs.

We downloaded Linkage Mapper software for ArcMap (ArcMap, 2022) and classified LCDB landcover categories for their likelihood to impede or promote tūī movement (according to literature and expert opinion). The top two categories were deemed ideal tūī nesting habitats (See Appendix A.1). Only patches over 1ha in size were selected, as literature showed this as the minimum size of effective habitat patches (Bergguist, 1989). In ArcMap, these were combined with the reclassified landcover (resistance) raster, using the Linkage Mapper toolbox to produce a tūī movement corridor map.

2.3.3 Site Suitability Inputs

Tūī corridors, aspect, Euclidean distance to core habitats, rainfall, and slope, were all used to determine planting suitability. We reclassified these datasets into nine breaks, with nine being best for planting and one being worst for planting. First, we derived the slope from the DEM using the slope function. Lower angles are better suited for planting (Boffa Miskell Limited, 2007); therefore, slopes below 45 degrees were reclassified into nine categories (Table 1), while slopes above 45 degrees were excluded. Next, we created an aspect layer using the DEM and the aspect function. Literature and consultation with ecologists informed us that locally, southern aspects are best suited for planting, while northern aspects are least suited (Geroy et al., 2011; Moeslund et al., 2013; Radcliffe & Lefever, 1981). Reclased aspect values are shown in Table 1. Next, we used the Euclidean distance tool to create buffers around core tūī habitats. Areas closer to core habitats are more suited to planting (Pejchar et al., 2018), so they received higher rankings than areas further away (Table 1). Areas of high precipitation are also better suited for planting (Meurk, 2006). The precipitation raster was therefore reclassified into nine equal intervals, assigning a higher rank to areas of high precipitation (Table 1). Finally, research showed that areas with higher connectivity are more beneficial for planting (Innes et al., 2022). We therefore reclassified the tūī corridor connectivity into nine categories using quantile breaks, with areas of high connectivity ranked higher (Table 1).

2.3.4 Site Suitability Analysis

After reclassifying the five input rasters, we combined them in the Weighted Overlay tool. Slope, aspect, distance to core habitats, and rainfall received equal weightings of 21%, while corridor connectivity received a lower weighting of 16%. We ranked corridor connectivity lower as, unlike terrain and climate factors, it plays no part in planting survival. Furthermore, equal weighting led to connectivity obscuring the other factors. The four remaining inputs were equally weighted because there was no information to suggest a priority order. For slope, we classified angles above 45 degrees as restricted because they are too steep to plant safely.

Table 2: Table showing the reclassification rankings of slope, aspect, distance to core habitats, precipitation, and corridor connectivity. 9 = most suitable ranking, 1 = least suitable ranking.

Reclassification Ranking	Slope (degrees)	Aspect (cardinal direction)	Distance to core habitats (m)	Precipitation (mm/yr)	Corridor Connectivity
9	0 - 5	South	0 - 500	2221 - 2439	High
8	5 - 10	South-West	500 - 1000	2003 - 2221	|
7	10 - 15	South-East	1000 - 2000	1786 - 2003	|
6	15 - 20	West	2000 - 3500	1568 - 1786	|
5	20 - 25	East	3500 - 5500	1350 - 1568	|
4	25 - 30	North-West	5500 - 8000	1132 - 1350	|
3	30 - 35	North-East	8000 - 11000	914 - 1132	|
2	35 - 40	North	11000 - 14500	696 - 914	|
1	40 - 45	North	14500 - 19000	479 - 696	Low

3. Results

3.1 Corridor Mapping

3.1.1 Landcover

Ranking and reclassifying LCDB landcover classes (Figure 1**Error! Reference source not found.**) displayed areas with highly suitable dark and light green vegetation and those with less suitable vegetation in orange and red. Appendix A.1. displays the classes and reasoning behind the suitability for each class. Ōtautahi is ranked moderately low due to high urbanisation. However, it is essential to note that low-ranked land cover can become tūī habitat.

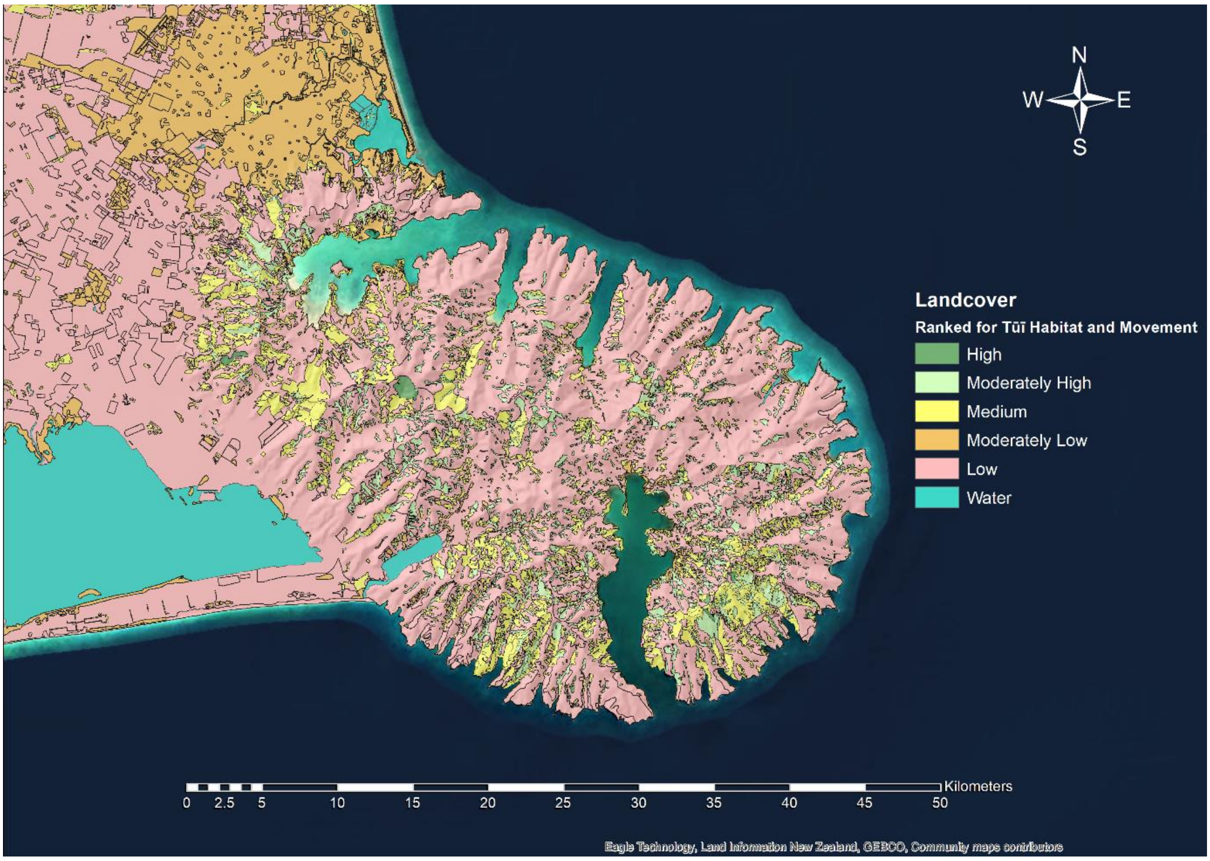

Figure 1: Suitable existing landcover for tūī Habitat. LCDB v5.0 – Land Cover Database version 5.0, Mainland, New Zealand.

3.1.2 Core Tūī Habitats

Indigenous forests and broadleaved indigenous hardwoods were selected from the landcover layer (Figure 2) as the best tūī habitat (purple). In Figure 2, these core habitats are fragmented across Horomaka, with clusters forming primarily in Southern areas, near Hinewai reserve, and on southern aspects of the Port Hills.

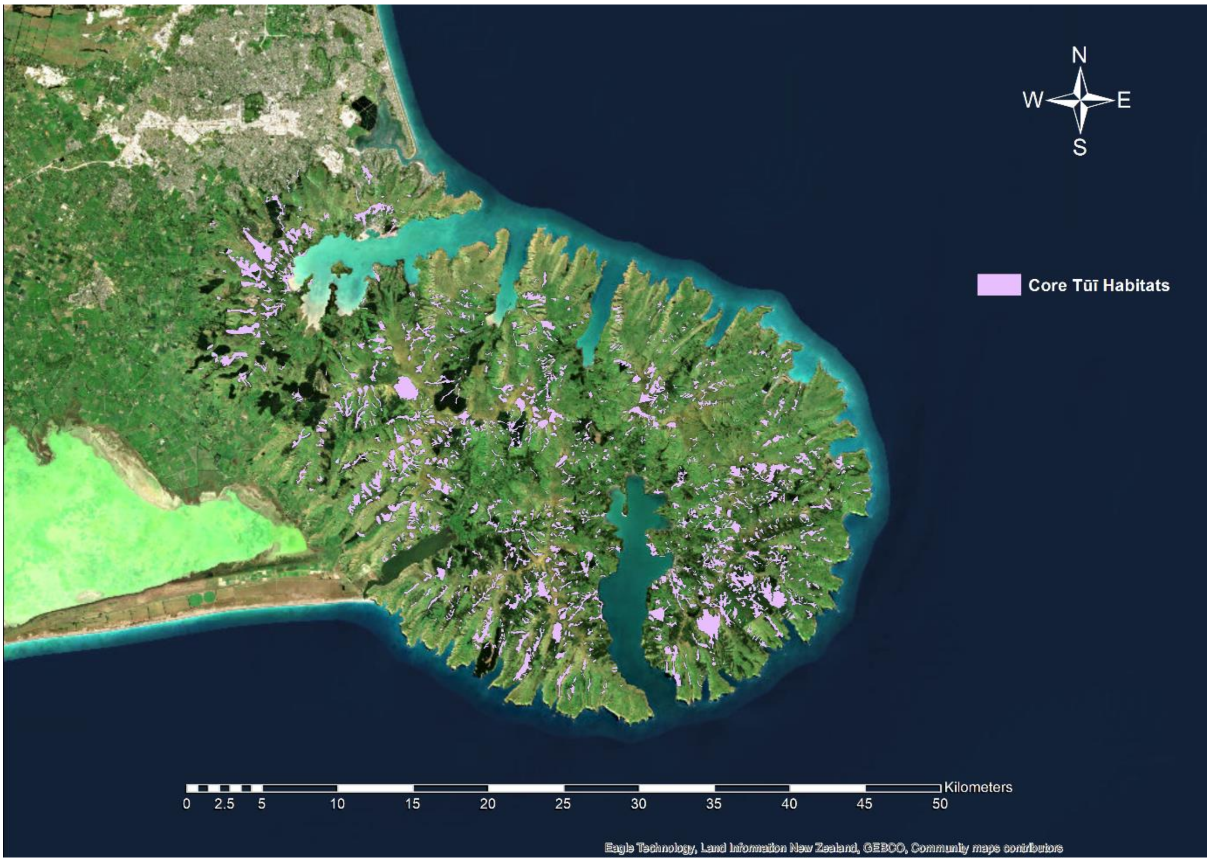

Figure 2: Core Tūī Habitats, indigenous forest and broadleaved indigenous Hardwoods, derived from LCDB v5.0. Core habitats are 1ha or larger.

3.1.3 Corridor Connectivity

The majority of Horomaka has well-connected tūī habitat (Figure 3). However, the density of corridor connectivity shows various 'sources' and 'sinks.'. The objective of this map was to map connectivity according to natal dispersal, which is the process of young animals permanently leaving the adults to search for a new habitat (Studds et al., 2008). 10km was used as a metric for calculating corridor lengths in Linkage Mapper, correlating to the maximum natal dispersal distance identified in the literature (Innis et al., 2022)

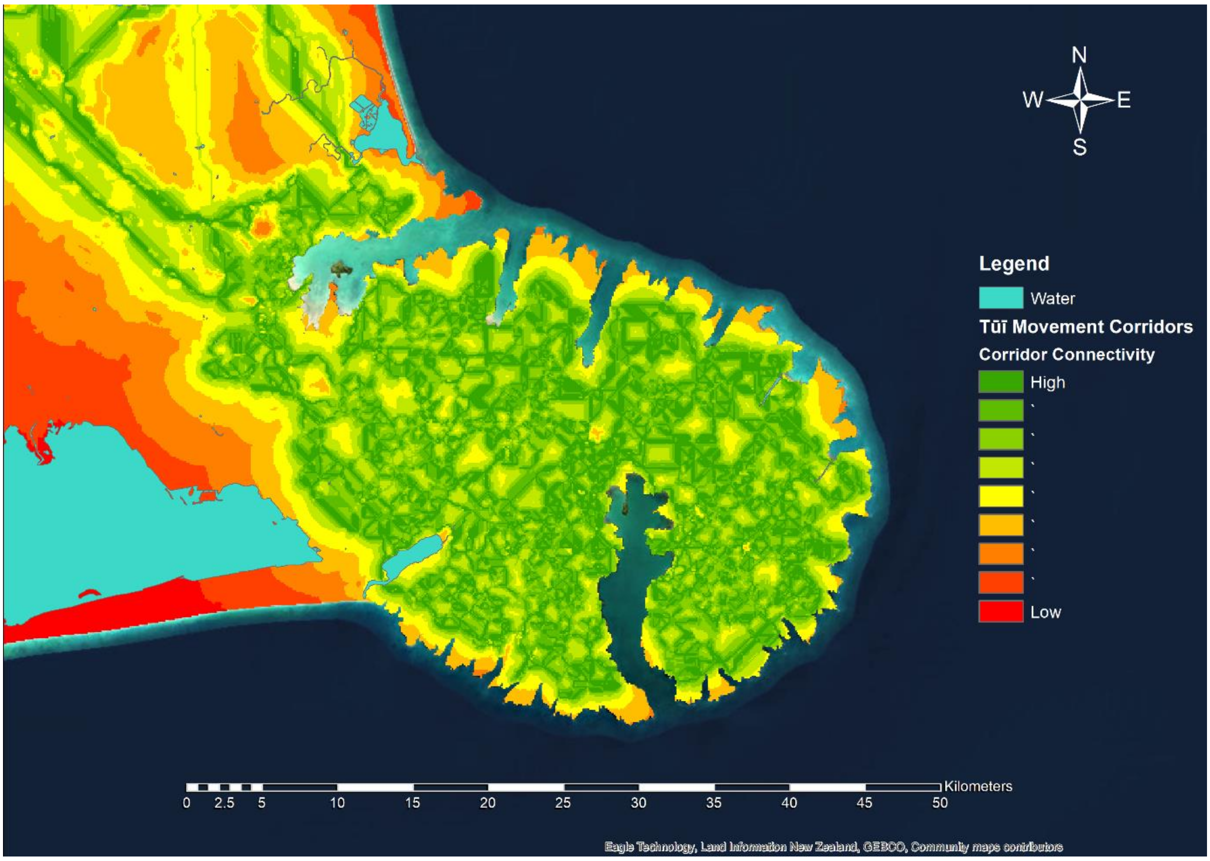

Figure 3: Tūī corridor connectivity network. Based on existing core tūī habitats, green shows the accessibility between patches for tūī.

3.2 Site Suitability Inputs

3.2.1 DEM

This DEM produced elevation map (Figure 4) was used as an intermediate step to produce slope and aspect data.

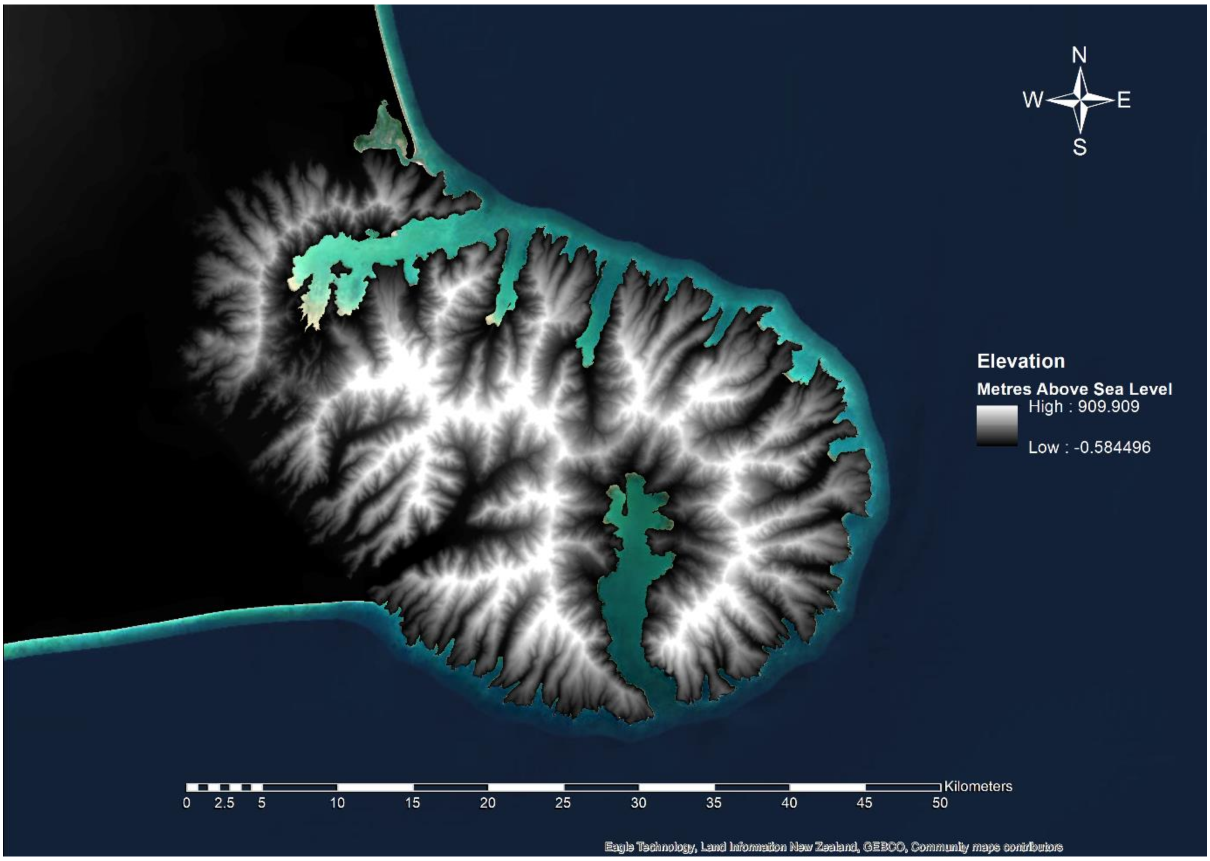

Figure 4: Digital elevation model (DEM) of Banks Peninsula. LINZ.

3.2.2 Slope

Figure 5 shows that slopes in the south are generally steeper, while at the head of the harbours, the angle is lower. The slope is lowest in the valleys, along the crest of the radiating spurs that characterise the Peninsula, and steepest off the sides of spurs.

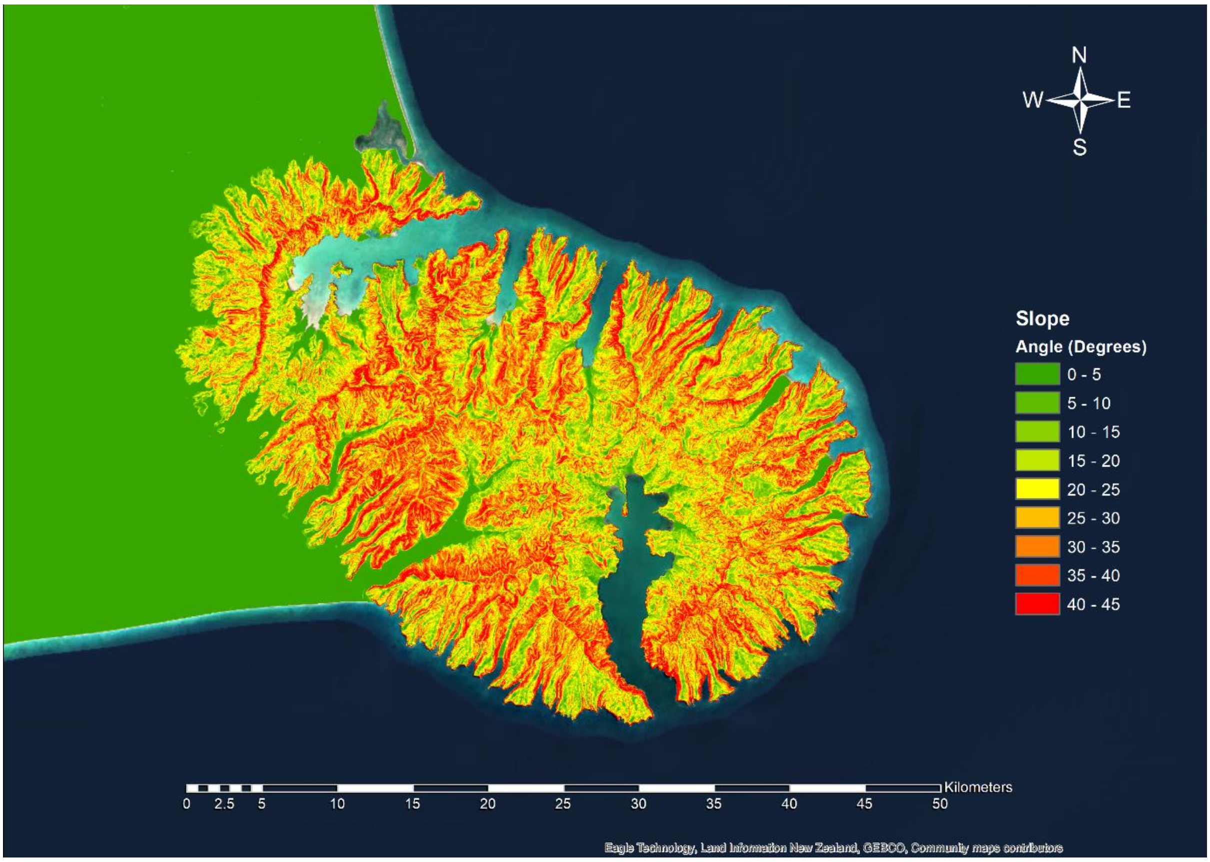

Figure 5: Based off the DEM, the slope in degrees across the Banks Peninsula.

3.2.3 Aspect

In Figure 6, a distinct aspect pattern is evident in the Port hills, with the Ōtautahi side of the Port Hills facing north to west. However, the Whakaraupō side faces east to south, which has heavily skewed both existing forest distribution (Figure 2) and modelled terrain/climate characteristics (Figure 9) in favour of the Whakaraupo side. The rest of the Peninsula displays a more diverse mix of aspects.

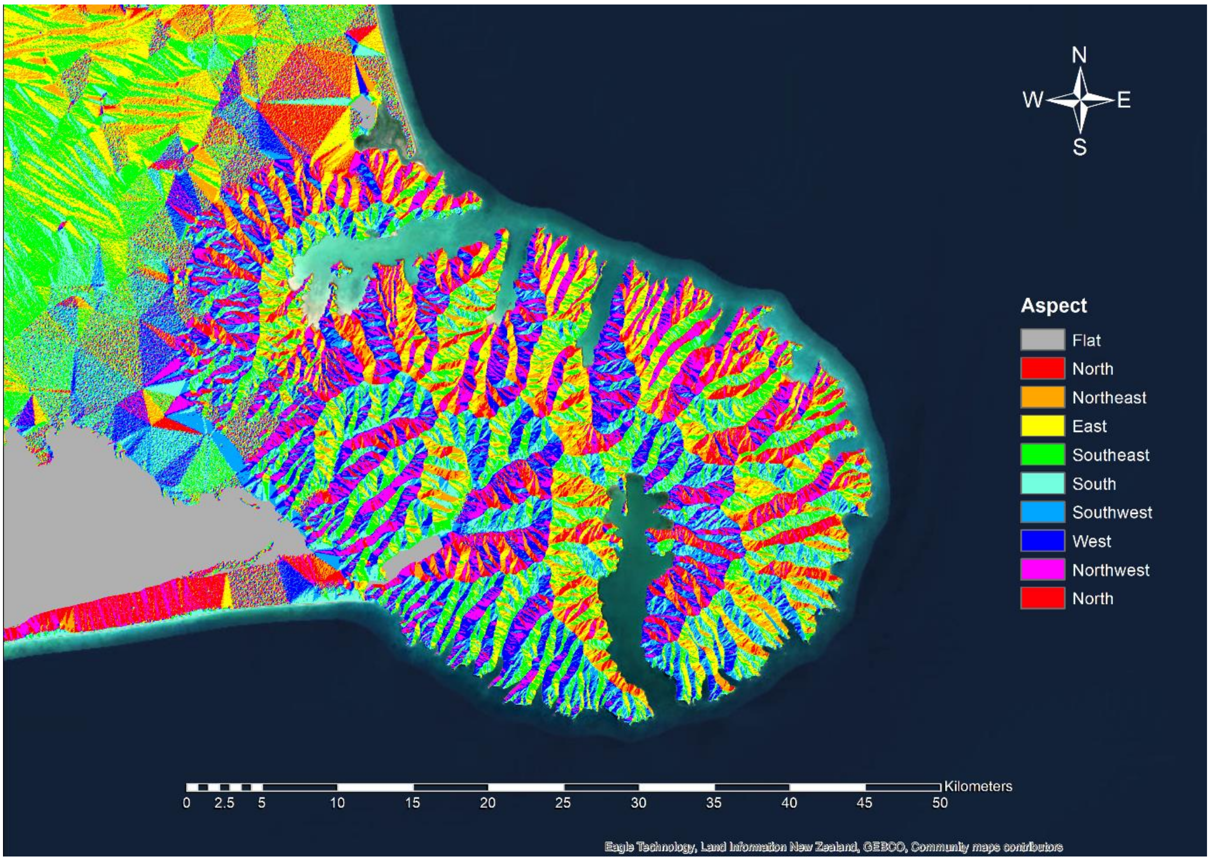

Figure 6: The aspect of Banks Peninsula. Based off the DEM. The colours represent the direction the terrain is facing.

3.2.4 Buffer Distances

Figure 2 shows the core habitat areas scattered around the Peninsula; Figure 7 calculated the distance around each core habitat. Green is between 0-500m, and red expands to 14,500-19,000m. Across the whole of Horomaka, core habitat patches are within 2,000m of each other. Gap spacing increases drastically on the plains.

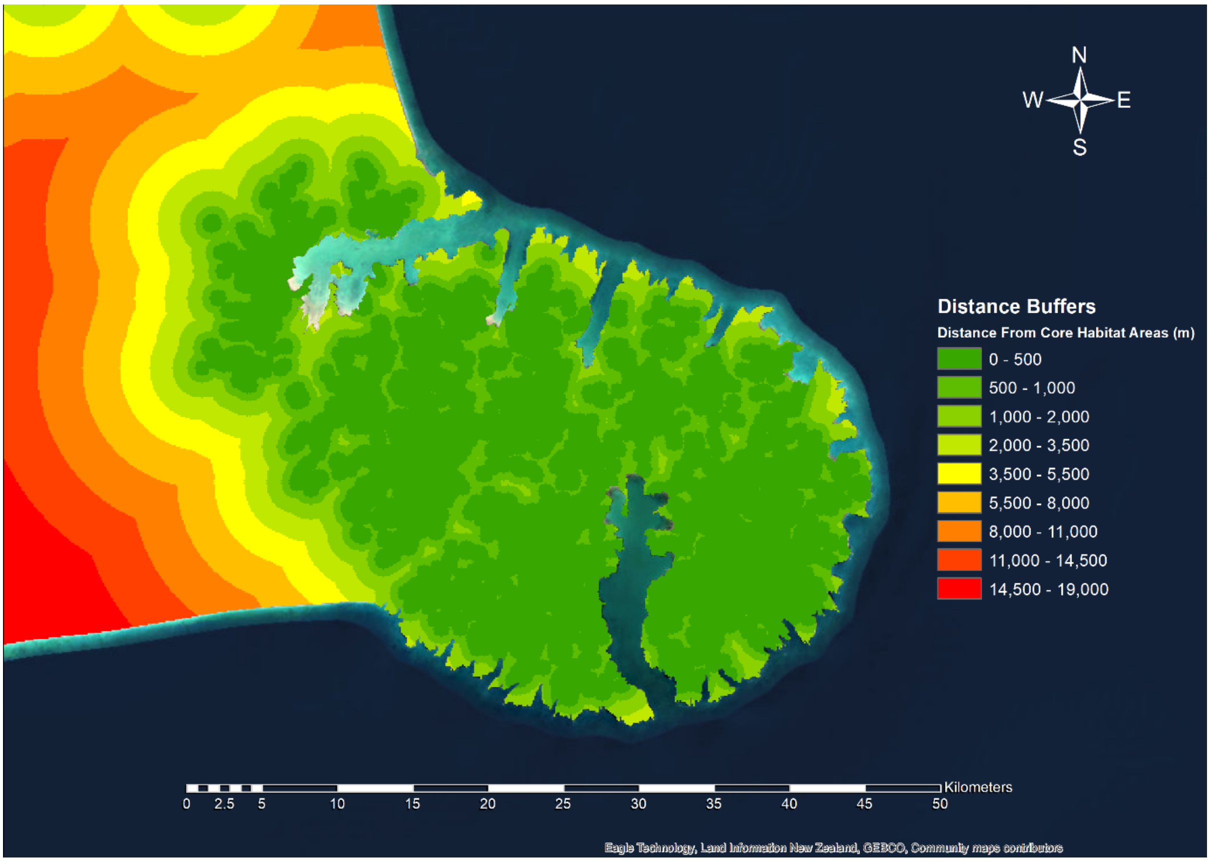

Figure 7: Euclidean distance buffers from core habitat areas.

3.2.5 Precipitation

The precipitation model (LRIS, 2022) suggests high spatial variability of rainfall across Horomaka, ranging from 480mm/yr to 2400mm/yr maxima in high south-eastern areas and very isolated northern areas around Mt Evans and Herbert, as seen in Figure 8. This indicates presence of distinct microclimates. Precipitation consistently increases with elevation.

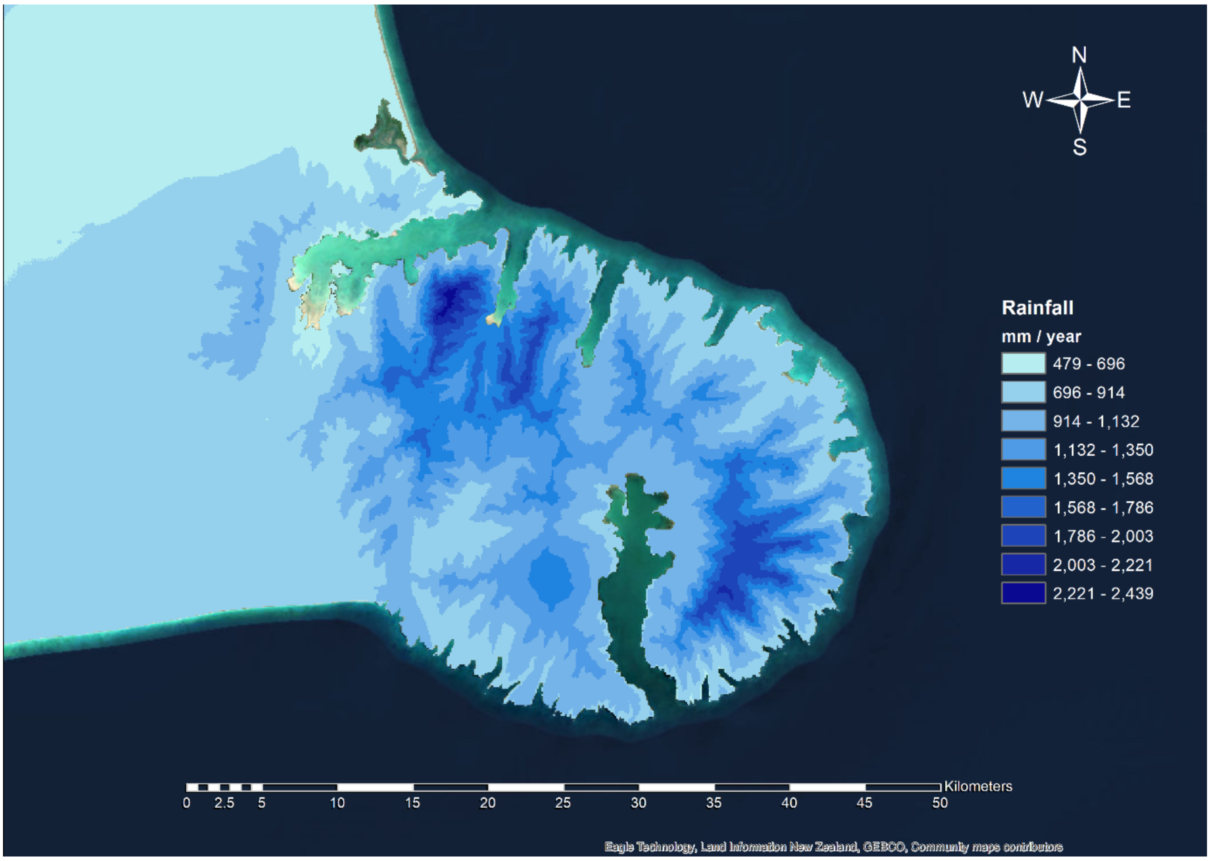

Figure 8: Precipitation (mm/year) across the Banks Peninsula (Leathwick et al., 2002).

3.3 Site Suitability

Figure 9 shows suitability for restorative native planting and enhancing Tūī dispersal and populations. It constitutes the main output of our analysis. All the previous data displayed above were used to create this suitability map. Suitable planting sites frequently appear in central and southern Horomaka. However, earlier findings have shown the importance of habitat improvement to the northwest of the Peninsula, which may presently act as a population sink. Suitable sites cluster around Hinewai reserve and on polar aspects surrounding Lyttleton harbour.

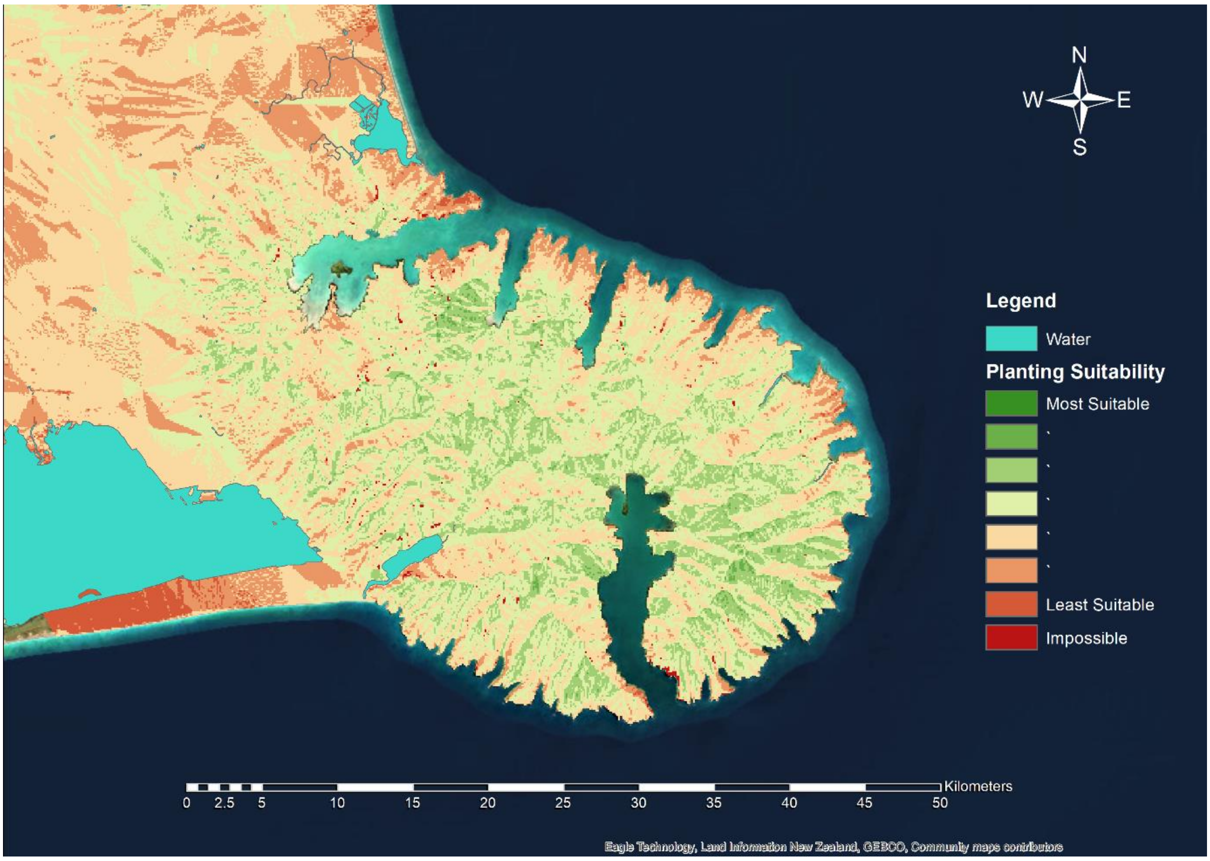

Figure 9: The final output of planting site suitability across Banks Peninsula.

3.4 Predator Control

Predation by ship rats and possums is a primary problem along with food competition, habitat area and other factors (Innes et al. 2010). Figure 10 compares tūī sightings iNaturalist with current trap locations for pest control in the Port Hills. In both Bell (2008) and Fitzgerald (2019), the evidence shows that efforts for predator-free environments can contribute to an increase in tūī populations. This visual comparison justifies that pest control is crucial in determining tūī populations.

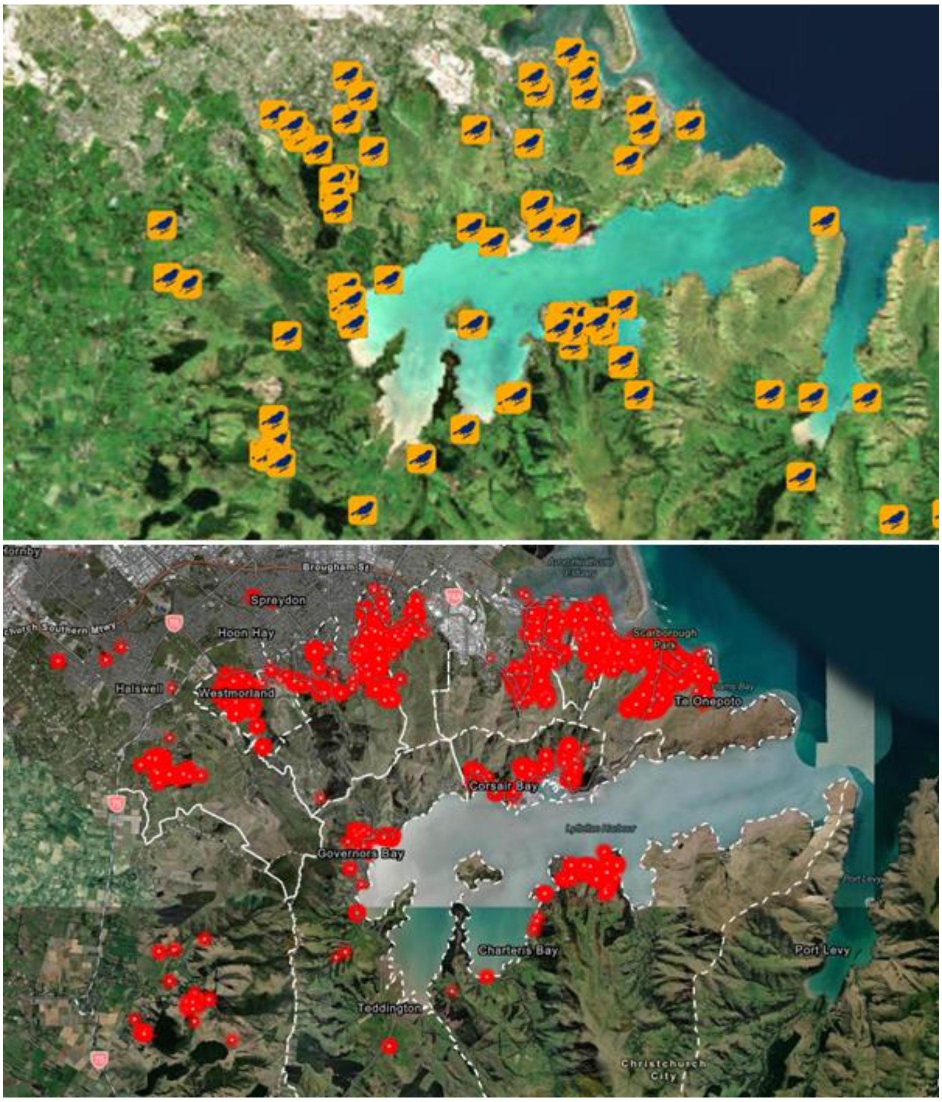

Figure 10: Tūī sightings (top), iNaturalists contributors, 2022, and Predator control (bottom) Predator Free Port Hills, 2022.

4. Discussion

4.1 Site Suitability Map – Spatial Implications

The site suitability map (Figure 11) reveals interesting spatial patterns in planting site suitability. Suitable planting sites reduce in number to the north-west, reflecting less suitable landcover for tūī movement, fewer large core habitat patches, and more challenging planting conditions due to a drier microclimate. These factors also cause sharper suitability contrasts near the city (Figure 11A) than in central and south-eastern Horomaka (Figure 11E, Figure 11F). These are essential considerations for TCF, showing that closer to the city, greater care is required during site selection, with ideal sites limited and adjacent to highly unsuitable sites.

The site suitability map shows an association between planting site, suitability and tūī populace. Hinewai (Figure 11B) and the broader Akaroa area – currently the centre of Horomaka tūī population - show higher proportions of suitable planting sites than the Port Hills, where tūī are scarce. The higher proportion near Horomaka may be due to more core habitat area (Figure 2) and a surrounding matrix of more suitable landcover for tūī, providing higher connectivity. Alternatively, this could be an artefact of proximity to the 2009 translocation site. The most significant gap in core habitats lies along a Whakaraupō - Gebbies pass axis. This gap is unlikely to pose an issue due to tūī's high dispersal capabilities (Innis et al., 2022). However, it might inhibit connectivity for less mobile native birds, which may benefit from planting near Gebbies Pass.

Literature (Pejcharet al., 2018) suggests that planting adjacent to existing core habitats is more valuable than planting in isolation. This was also reflected in our research, with areas of high planting suitability most often encountered proximal to core habitat patches (Figure 11D).

A large area of highly suitable planting habitat is on the shadier slopes of Mt Evans (Figure 11B). Given tūī's high mobility, this is an example of a high-potential planting location that could create a large habitat patch for a satellite population, forming a steppingstone for natal dispersal across to existing and potential habitat in Lyttleton and towards Ōtautahi (Figure 11A), where a promising high-suitability habitat patch is suggested in the Heathcote Valley. However, TCF may find that modelled suitable locations near urban centres may not allow planting due to economic and human pressures.

The suitability map indicates that south aspects of the Port Hills also appear to comprise an area of suitable existing and potential habitat close to Ōtautahi. The expert opinion confirms this. The lack of a resident population here supports the expert opinion that factors other than habitat are currently the chief controls on Horomaka tūī population.

A peripheral ring of lower-suitability planting terrain followed the peninsula's shoreline (Figure 11C). This ring is likely attributed to lower rainfall at low elevations, and on the northwest side greater agricultural modification may be inferred from the reduced area of core habitat polygons and suitable planting sites. Precipitation had one of the most prominent influences on the site suitability map due to well-defined spatial zonation across Horomaka. Greater precipitation ensures higher soil moisture, reducing restoration planting failures from drought stress.

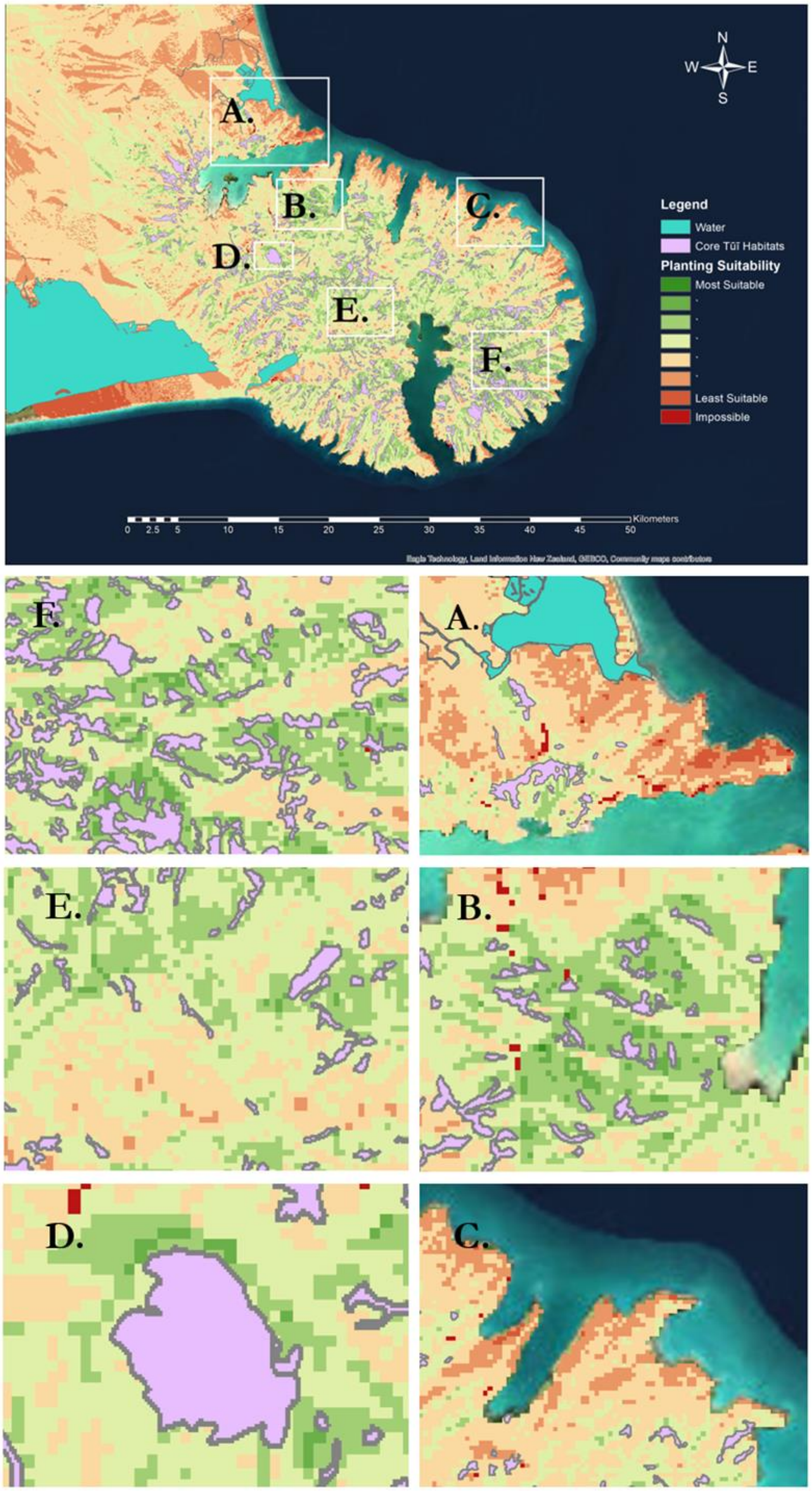

Figure 11: Site Suitability Sub map. A through D, showing specific areas of interest across Banks Peninsula.

4.2 Corridors and Connectivity

Enriching vegetational populations and compositions on Horomaka will facilitate the presence of tūī in Ōtautahi through the connectivity process of cross-habitat spillover. Cross-habitat spillover encompasses foraging and dispersal, which drive an organism between areas of suitable habitat to avoid resource competition (Blitzer et al., 2012; Innes et al., 2022; Tscharntke et al., 2012). Tūī are weakly gap limited (Figure 12) with high natal dispersal (10km) and foraging distances (5-35km), making spillover given high abundance (Fitzgerald et al., 2019; Innes et al., 2022). Habitat connectivity aids in dispersal by increasing access to resources, enabling the persistence of populations (Innes et al., 2022). Spillover is strongest when forest fragments are larger, and organisms' numbers are high. Therefore, increasing habitat area and patch size across the peninsula will aid spillover into the city (Martensen et al., 2012). Tūī have shown a preference for older vegetation, supporting Noe et al. (2022) finding that planting adjacent to existing core habitat is more valuable. TCF should keep in mind that a 10-year lag has been found between native plantings and tūī use (Elliot Noe, 2022).

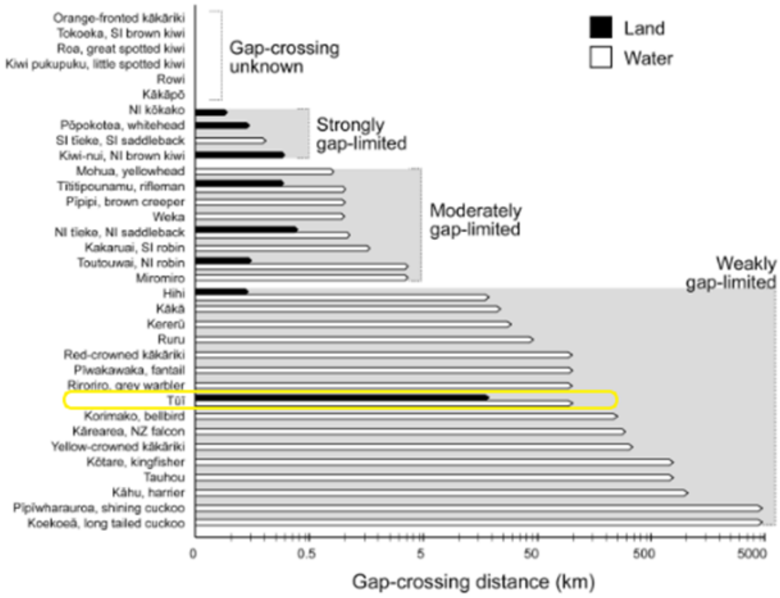

Figure 12: Tūī gap-crossing highlighted in yellow, Innis (2022).

4.3 Climate

Ōtautahi and Horomaka have dry climates, with annual average precipitation of 619mm/yr in Ōtautahi (Macara, 2016). In summer, the area experiences depressed rainfall, arid conditions, and frequent droughts; while anthropogenic climate forcing also contribute to long-term rainfall reduction on the eastern side of the South Island (Meurk, 2006; MfE, 2020). Distinct plant assemblages typically result from spatially varying environmental factors, such as precipitation and sunlight (Barry & Blanken, 2016; Harrison et al., 2020; Oke et al., 1988; Yang et al., 2020). This is true for Horomaka, where the experts we interviewed all agreed that water availability and soil moisture retention are the critical controls on the success of native revegetation projects. Summer survivability is the crucial botanic question in determining planting site suitability, and this is heavily reflected in the site suitability map.

4.4 Microclimate, Aspect and Vegetation

Microclimate strongly shape species compositions between aspects, due to the influence of aspect & slope on solar insolation (Gallard et al., 2009; Geroy et al., 2011; Maler & Moral, 2018; Harrison et al., 2020; Moeslund et al., 2013; Oke et al., 1988; Radcliffe & Lefever, 1981). South aspects and lower slope angles retain more moisture (Geroy et al., 2011; Moeslund et al., 2013; Radcliffe & Lefever, 1981), which experts agreed was the essential control on restoration planting. Furthermore, less interspecific competition for light on southern aspects encourages diverse compositions (Geroy et al., 2011; Moeslund et al., 2013; Radcliffe & Lefever, 1981), providing more food diversity for tūī. Including planting on both north and south aspects is key to higher local-scale diversity, as each aspect can support species that the other cannot, increasing the range of available food and habitat (Hammill et al., 2018; Marler & Moral, 2018). This finding was not modelled due to time constraints, but the implication is that planting near a change in aspect will benefit tui more than planting far from aspect boundaries.

4.5 Predator Control and Future Efforts

Introduced mammalian predators limit New Zealand bird numbers (Fitzgerald et al., 2019). To mitigate predation and increase populations on Horomaka, effective predator management is required (expert opinion). Pest control tools to protect tūī include traps, poisoning and pest-fencing (Innes, 2018). Research shows tūī abundance increases within and around pest-free areas by natural spillover (Ball, 2008; Fitzgerald et al., 2019). Tūī 's strong mobility (Figure 12) allows them to utilise urban gardens for food and habitat resources (Bell, 2008; Fitzgerald et al., 2019). Predator management needs to be incorporated within the city and span across a more significant portion of Horomaka to facilitate a sustainable tūī presence in Ōtautahi. To increase spillover success, Horomaka needs ongoing, overarching pest management strategies to mitigate source-sink dynamics, whereby tūī move from an area of favourable conditions (e.g. Hinewai) to an area where mortality exceeds their ability to reproduce (Fitzgerald et al., 2019; Innes, 2022). While the planting suitability map (Figure 9) shows Christchurch City as less suitable, further planting across Banks Peninsula will improve the planting suitability of the city.

4.6 Limitations

Our most significant limitations were time and literature scarcity. Consequently, our GIS analysis and Mana Whenua engagement were less than desired, and we could only focus on Horomaka, deeming detailed analysis of Ōtautahi habitat outside our scope. Tūī-specific literature scarcity was compensated by interviewing experts and weighing findings relevant to other birds. While credible, this lacks the objectivity of a study building heavily on peer-reviewed literature. Furthermore, a more rigorous structure to interviews, and a systematic manner of recording findings, would have further increased the utility of expert opinion.

The size of our study area precluded primary data collection or ground-checking landcover areas for tūī habitat, food, or presence. We viewed iNaturalist observations, however clusters of tūī population are skewed towards clusters of human population and can only be used inferentially. The extensive area also limited us to mid-resolution GIS analysis, using only data sourced online. Thus, mapping results are based on a mix of secondary data (both observational and modelled), introducing unknowns around the methods by which these data were collected and organised.

The GIS analysis presented many limitations, particularly with technical ability and data. For example, the most current landcover data (LCDB 5.0, Landcare Research) was from 2018, excluding the past four years' planting initiatives. The rainfall model used (LRIS, 2022) had higher localised values than a recent NIWA map (Macara, 2016). In addition, our expertise was limited, and analysis utilised computationally heavy tools that were new to us, causing difficulties. Despite literature review and expert opinion, subjective decisions were essential at points during analysis (e.g., specifying choosing variability weightings). Accordingly, we suspect our findings are significantly less robust than if an experienced ecologist performed the same analysis.

Our analysis also excluded many variables - for example, TCF and other organisations' areas of existing planting initiatives - as we could not acquire the necessary data. Information on existing land ownership and pest control would also be helpful to TCF but were outside our studies' scope. Several additional factors that could have increased the accuracy of planting suitability analysis were also overlooked– for example, after analysis completion, we were informed that soil depth and elevation are also important variables.

We noticed an error in our GIS method following analysis with the reclassification of aspect. As an artefact of GIS program requirements, the north was split into two, and the nine categories (NW, N, NE...) were each assigned 40° each. Aspect values should, ideally, be split into eight octants of 45° each, except for north aspects, which should have received 22.5°. This oversight means that aspect categories do not precisely represent the cardinal directions and that northerly aspects are over-represented. However, the aspect layer only holds a 21% weighting for the weighted overlay, diluting the classification inaccuracy with only minor effects on the planting suitability map. Furthermore, an even split assumes that aspect has a linear impact on soil moisture, which may not reflect reality. The error slightly reduces the scientific precision of this work, but not its real-world applicability.

Our studies' limitations impact the accuracy and reliability of our results. Therefore, when using the results to inform future planting, consideration of this factor is suggested.

5. Conclusion

This study aimed to inform tūī restoration measures on Horomaka by TCF, with the end goal of establishing resilient satellite populations near Ōtautahi. A mixed-methodology approach showed that a high degree of habitat connectivity exists across the peninsula. However, a corridor model can be combined with terrain and climate data to map further planting site suitability across Horomaka comprehensively.

Key findings include:

- Effective, sustained predator management and year-round access to food species are the top priorities for tūī restoration.
- Increasing overall habitat area and connectivity are important secondary priorities.
- Tūī requires large habitat patches (>1ha) to facilitate natal dispersal.
- Patch size is more important than patch spacing. Restoration planting is most effective when it enlarges existing habitat patches.
- Increasing the source population in the Hinewai/Akaroa area is an essential first step.
- The planting site suitability map shows promise for optimising planting locations towards returning tūī to Ōtautahi.

Further research priorities include urban tūī habitat, autumn/winter food species availability in Ōtautahi, and strategies to increase predator management efficacy across Horomaka.

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8. Appendices

Appendix A. Landcover Class Rankings

Following literature review and expert interviews, landcover database v5.0 (LRIS, 2022) landcover categories were ranked according to their ability facilitate tūī movement. The resultant table was checked by ecologists, before final adjustments were made and verified.

Table A.1. Landcover Class Rankings, informed by literature and expert opinion.

Landcover Category	LCDB V5.0 Definition	Top ranked (100% effective)	High Ranked	Mid-ranked	Low-ranked	Lowest Ranked (greatest resistance)	Rationale
Indigenous Forest	Tall forest dominated by indigenous conifer, broadleaved or beech species.	x					Historic natural primary habitat. Range of food species, flowering at different times
Broadleaved Indigenous Hardwoods	Lowland scrub communities dominated by indigenous mixed broadleaved shrubs such as wineberry, mahoe, five-finger, Pittosporum spp, fuchsia, tutu, titoki and tree ferns. This class is usually indicative of advanced succession toward indigenous forest.		x				Natural habitat: next best to complete mature native forest
Mixed Exotic Shrubland	Communities of introduced shrubs and climbers such as boxthorn, hawthorn, elderberry,			x			Potential food species and shelter

	blackberry, sweet brier, buddleja, and old man's beard.						
Manuka and/or Kanuka	Scrub dominated by mānuka and/or kānuka, typically as a successional community in a reversion toward forest. Mānuka has a wider ecological tolerance and distribution than kānuka with the latter somewhat concentrated in the north with particular prominence on the volcanic soils of the central volcanic plateau.			x			Limited food potential for Tui, but short Spring flowering season, and some shelter, and mid-canopy height.
Exotic Forest	Planted or naturalised forest predominantly of radiata pine but including other pine species, Douglas fir, cypress, larch, acacia and eucalypts. Production forestry is the main land use in this class with minor areas devoted to mass movement erosion-control and other areas of naturalised (wildling) establishment.			x			Dr Molles: Eucalyptus are a preferred food source. Mature plantations often develop native understory. Tall plantation trees may function as songposts in mosaic landscapes.
Gorse/broom	Scrub communities dominated by gorse or Scotch			x			Potential food species during flowering season.

	broom generally occurring on sites of low fertility, often with a history of fire, and insufficient grazing pressure to control spread. Left undisturbed, this class can be transitional to Broadleaved Indigenous Hardwoods.						Nursery potential for natives
Fernland	Areas dominated by New Zealand flax usually swamp flax (harakeke) in damp sites but occasionally mountain flax (wharariki) on cliffs and mountain slopes.			x			Important Tūī food species. Input from Dr Molles: "could be attractive to tui, but the patches would need to be either very large or quite close to other food resources to be really useful"
Deciduous Hardwoods	Exotic deciduous woodlands, predominantly of willows or poplars but also of oak, elm, ash or other species. Commonly alongside inland water (or as part of wetlands), or as erosion-control, shelter and amenity plantings.			x			Decent shelter, songpost and nesting potential; food species potential but details unknown.
Grey Scrub / Matagouri	Scrub and shrubland comprising small-leaved, often divaricating shrubs such as matagouri, *Coprosma* spp, *Muehlenbeckia* spp., *Casinnia* spp., and				x		Dr Molles: "Possibly an additional resource that might be used if they are adjacent to more preferred habitat, but they won't be a draw…tight

	Parsonsia spp. These, from a distance, often have a grey appearance.						divaricating shrubs that tui are probably a bit too big to exploit effectively.”
Built-up area	Commercial, industrial or residential buildings, including associated infrastructure and amenities, not resolvable as other classes. Low density ‘lifestyle’ residential areas are included				x		Some back-yards have native plants that are a good food source for Tui
Urban Parkland/Open space	Open, mainly grassed or sparsely-treed, amenity, utility and recreation areas. The class includes parks and playing fields, public gardens, cemeteries, golf courses, berms and other vegetated areas usually within or associated with built-up areas.				x		Some parks have native planting like harakeke or kowhai
Herbaceous Saline Vegetation	Herbaceous wetland communities occurring in saline habitats subject to tidal inundation or saltwater intrusion. Commonly includes club rush, wire rush and glasswort, but not				x		Potential for thin (unmappable) bands of harakeke at margins (food source)

	mangrove which is mapped separately.						
Herbaceous Freshwater vegetation	Herbaceous wetland communities occurring in freshwater habitats where the water table is above or just below the substrate surface for most of the year. The class includes rush, sedge, restiad, and sphagnum communities and other wetland species, but not flax nor willows which are mapped as Flaxland and Deciduous Hardwoods respectively.				x		Dr Molles: "flax along water/wetland/park edges could be attractive to tui, but the patches would need to be either very large or quite close to other food resources to be really useful."
Orchard/Vineyard	Land managed for the production of grapes, pip, citrus and stone fruit, nuts, olives, berries, kiwifruit, and other perennial crops. Cultivation for crop renewal is infrequent and irregular but is sometimes practiced for weed control.				x		Possible food sources; trees for shelter/rest
Tall tussock grassland	Indigenous snow tussocks in mainly alpine mountain-lands and red tussock in the central North Island and locally in poorly-drained valley floors, terraces				x		Tussocks offer poor support or shelter for tui, and are not a known food source for tui, but may support isolated shrubs and small trees.

	and basins of both islands.						
Lake / pond	Essentially-permanent, open, fresh-water without emerging vegetation including artificial features such as oxidation ponds, amenity, farm and fire ponds and reservoirs as well as natural lakes, ponds and tarns.				x		Surrounding banks often have riparian vegetation beneficial to Tui
Estuarine Open Water	Standing or flowing saline water without emerging vegetation including estuaries, lagoons, and occasionally lakes occurring in saline situations such as inter-dune hollows and coastal depressions				x		Potential for thin (unmappable) bands of harakeke at margins (food source)
Rivers	Flowing open fresh-water generally more than 30m wide and without emerging vegetation. It includes artificial features such as canals and channels as well as natural rivers and streams.				x		Surrounding banks often have riparian vegetation beneficial to Tui
High Producing exotic grassland	Exotic sward grassland of good pastoral quality and vigour reflecting					x	No food, shelter or trees for rest

	relatively high soil fertility and intensive grazing management. Clover species, ryegrass and cocksfoot dominate with lucerne and plantain locally important, but also including lower-producing grasses exhibiting vigour in areas of good soil moisture and fertility.						
Low producing grassland	Exotic sward grassland and indigenous short tussock grassland of poor pastoral quality reflecting lower soil fertility and extensive grazing management or non-agricultural use. Browntop, sweet vernal, danthonia, fescue and Yorkshire fog dominate, with indigenous short tussocks (hard tussock, blue tussock and silver tussock) common in the eastern South Island and locally elsewhere					x	No food, shelter or trees for rest
Short-rotation Cropland	Land regularly cultivated for the production of cereal, root, and seed crops, hops, vegetables, strawberries and					x	Not conducive to Tui habitat or food

	field nurseries, often including intervening grassland, fallow land, and other covers not delineated separately						
Gravel or Rock	Surfaces dominated by unconsolidated or consolidated materialsgenerally coarser than coarse gravel (60mm). Typically mapped along rocky seashores and rivers, sub-alpine and alpine areas, scree slopes and erosion pavements.					x	Not conducive to Tui habitat or food
Sand or Gravel	Bare surfaces dominated by unconsolidated materials generally finer than coarse gravel (60mm). Typically mapped along sandy seashores and the margins of lagoons and estuaries, lakes and rivers and some areas subject to surficial erosion, soil toxicity and extreme exposure					x	Not conducive to Tui habitat or food
Surface mine or dump	Bare surfaces arising from open-cast and other surface mining activities, quarries, gravel-pits and areas of					x	Not conducive to Tui habitat or food

	solid waste disposal such as refuse dumps, clean-fill dumps and active reclamation sites.						
Transport Infrastructure	Artificial surfaces associated with transport such as arterial roads, rail-yards and airport runways. Skid sites and landings associated with forest logging are sometimes also included					x	Main roads etc. not conducive to Tui – also result in air pollution
Forest – harvested	Predominantly bare ground arising from the harvesting of exotic forest or, less commonly, the clearing of indigenous forest. Replanting of exotic forest (or conversion to a new land use) is not evident and nor is the future use of land cleared of indigenous forest.					x	Pine forests dominate over indigenous species and don't provide good food or habitat for Tui

Appendix B. iNaturalist Tūī Sighting Map

Georeferenced citizen science observations are collected in iNaturalist, and verified by biologists (Loarie, 2022). Using this method of citizen science, GPS-tagged locations of tūī observations built a partial understanding of tūī distribution and abundance across Horomaka (Figure B.1).

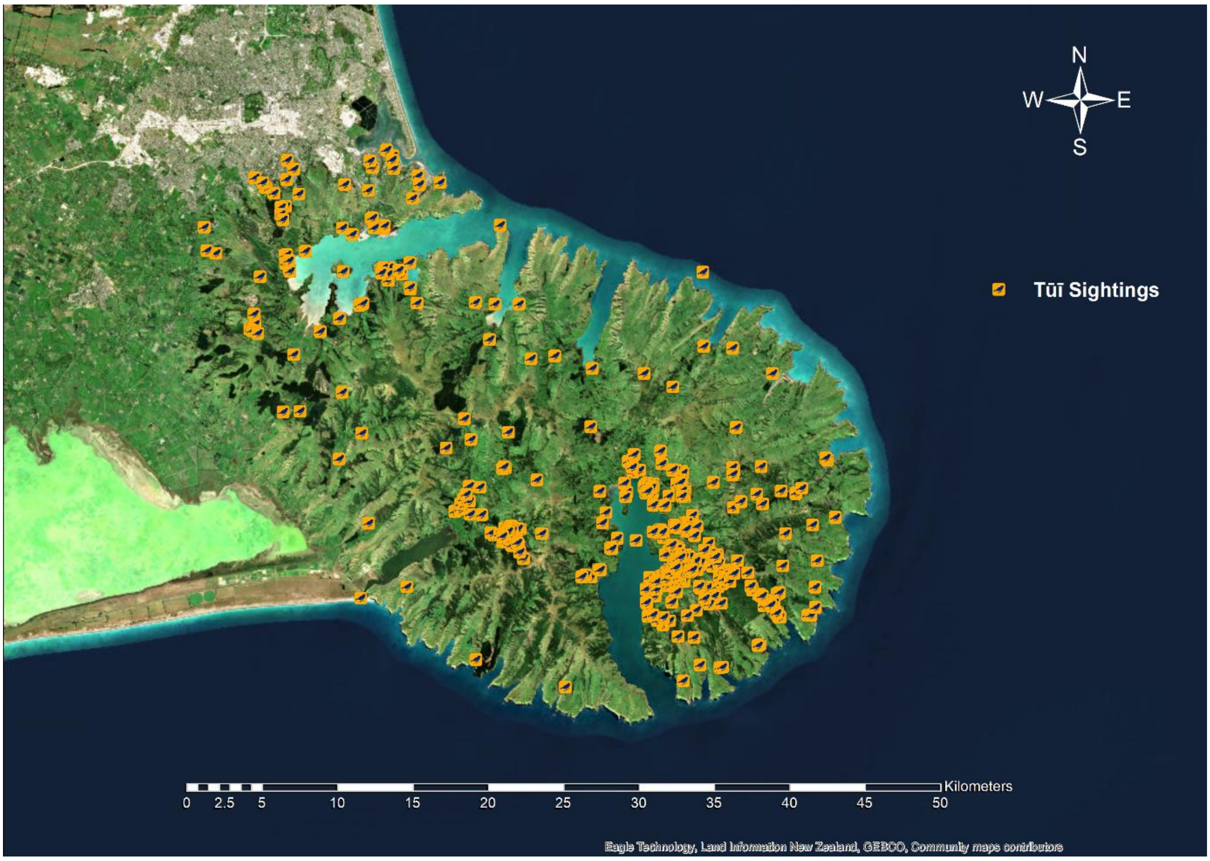

Figure B.1: Verified iNaturalist tūī sightings for Ōtautahi and Horomaka, 2009-2022 (iNaturalist contributors, 2022).

The main hotspots are around Akaroa, Okuti Valley and Hinewai reserve, along with some clusters around the port hills (Figure B.2). The area with the greatest number of tūī sightings was in Akaroa as there is a high density (indicated in red) in Figure B.2. Tūī sighting data is limited to human presence, so it therefore doesn't represent the full picture of Tūī dispersal across Banks Peninsula. For this reason, hot spot results weren't used for analysis, but simply for visual inference.

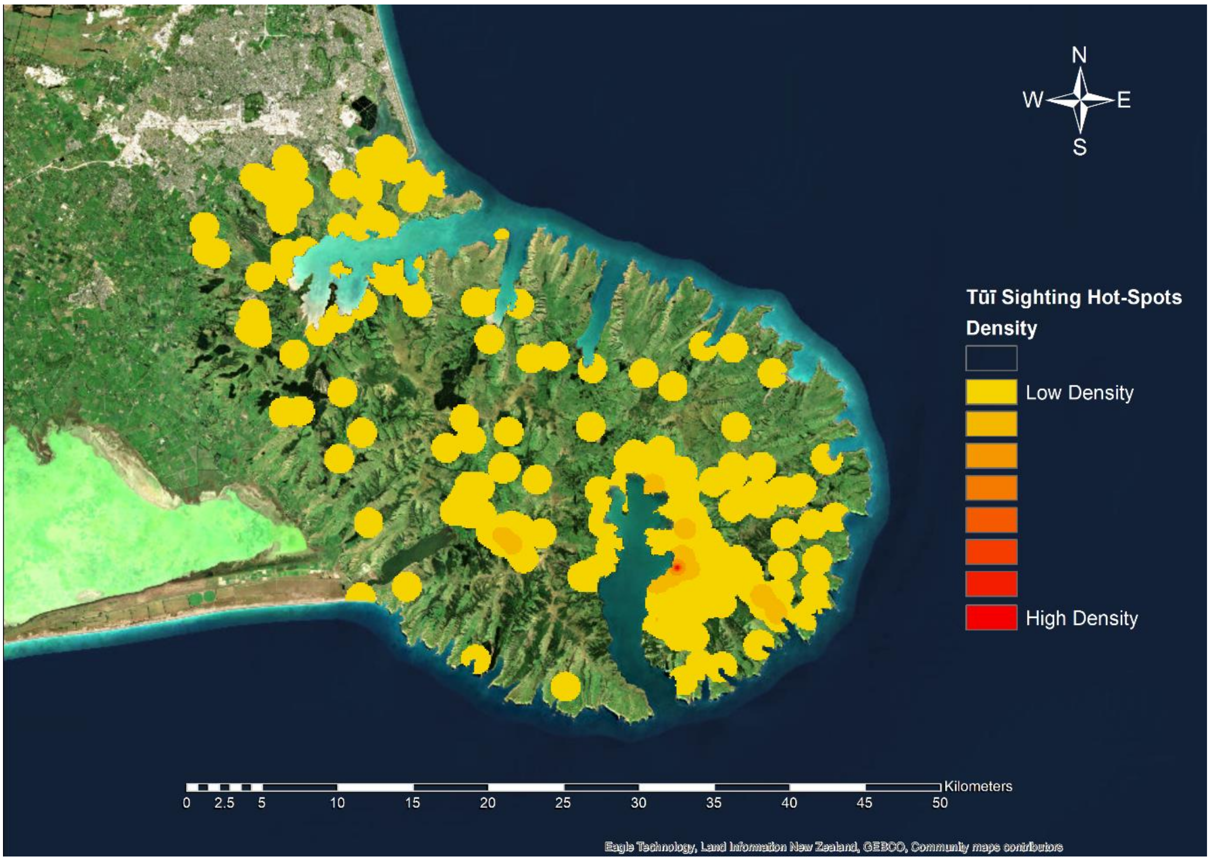

Figure B.2: Tūī Hotspot map showing areas of high tūī (observation) density.

Appendix C. Additional Resources for The Christchurch Foundation

- ArcGIS StoryMap (to be updated in week after submission)

https://storymaps.arcgis.com/stories/9687d1d633ed4a72957a0b1e4f07c0c5

- Expanded site suitability map outputs for easier spatial reference
- Google Earth file for planting suitability map
- Planting suitability map with hillhade and roads for better comprehension (Figure C.1).

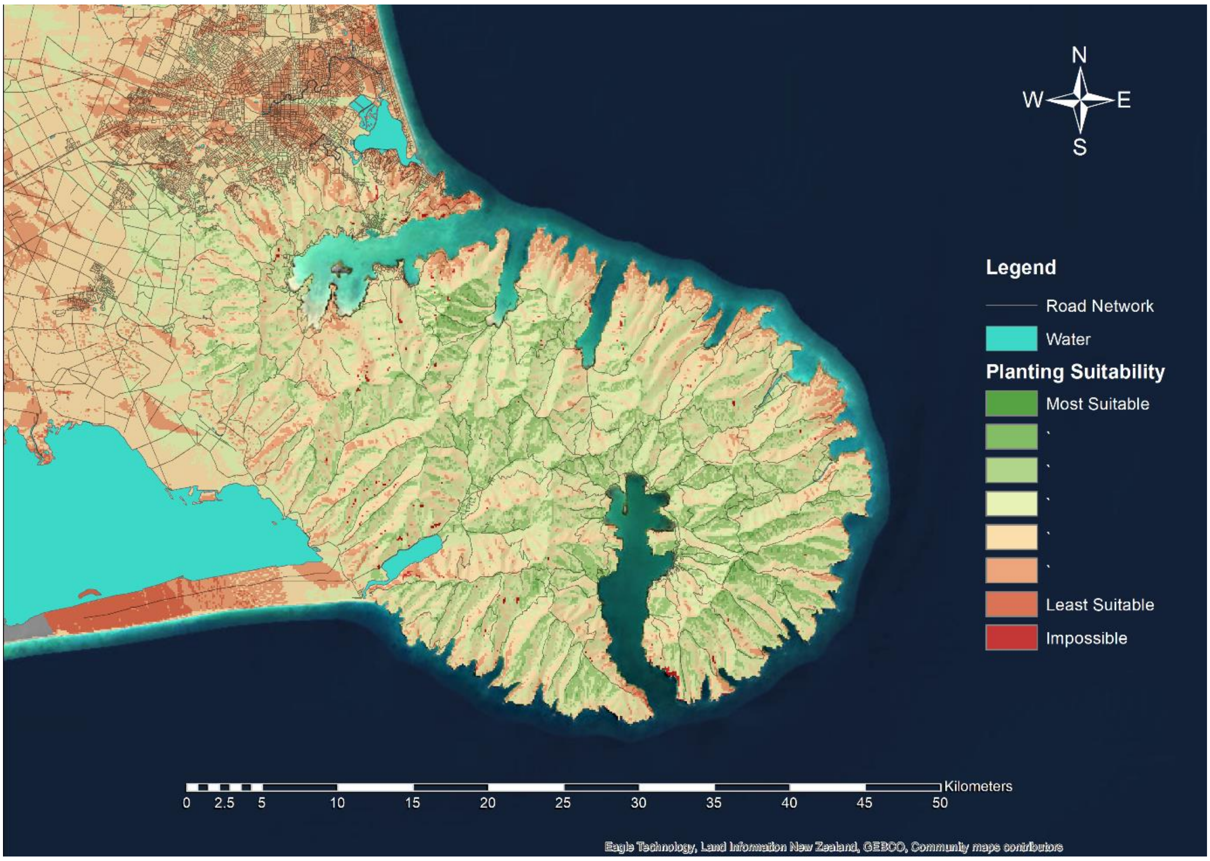

Figure C.1: Planting suitability map with hillshade and roads to increase ease of map comprehension.