ENVIRONMENTAL FACTORS INFLUENCING SURVIVAL OF POPLAR MATERIAL PLANTED FOR EROSION CONTROL ON HILL COUNTRY FARMS IN NEW ZEALAND

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Science
in
Agricultural Science

at Massey University, Manawatū,
New Zealand

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2023

Abstract

New Zealand has naturally high erosion rates, and space planting trees (most commonly poplars and willows species) in hill country landscapes is a widely used mitigation tool (Hicks & Anthony, 2001; Basher, 2013; Marden & Rowan, 1993; Hancox & Wright, 2005; Marden, 2012). The effectiveness of planting is, foremost, dependent on the survival and establishment of the trees. Much existing information on tree survival and the factors that influence survival is unpublished, with few studies having quantitively investigated survival rates and multiple potential explanatory variables. Moreover, there has not been a study to understand how different planting practitioners view the importance of survival and what influences their decisions of where, how, and what to plant in different conditions.

To explore these issues, this research involved a set of interviews which captured the current knowledge and views about tree planting and survival within a cross-section of New Zealand's North Island regional and district councils and scientists (Chapter 4). The interviews revealed a general consensus on the importance of trees in erosion mitigation, but mixed views regarding the importance of certain survival variables (e.g., where on the stems the poles are cut, duration of time between harvest and planting, or wind exposure). Differences likely reflect the different regional climate conditions and practitioner experience.

To enrich the quantitative data on tree survival in New Zealand hill country, a poplar planting trial was performed on three hill country farms in the North Island (Chapter 4). With climate considered to be one of the most important factors to affect survival, the trial tested the impact of different climatic conditions on plant survival over one planting season. Data from on-site climate stations and nearby NIWA (CliFlo) climate monitoring stations were used to analyse rainfall, temperature and solar radiation. The trial also tested the impact of morphometric variables (e.g., slope aspect, profile curvature, slope gradient and topographic position index), considered to affect the microclimate and soil conditions. At each farm, a north- and a south-facing slope susceptible to landslide erosion, was selected and each planted with 90 trees made up of three plant types; 30 3-m poplar poles planted using a pole driver, and 30 unrooted and 30 rooted poplar wands planted using a spade.

Overall survival across all three plant types (poles, unrooted wands, rooted wands) at all trial sites combined was high (90.4%). The highest survival across all plant types occurred at the Hawke's Bay site (93%) and the lowest occurred at the Taumarunui site (89%). South-facing aspects had slightly higher survival than north-facing aspects, of 90% and 89% respectively. The Wairarapa had no pole deaths which was attributed to experienced pole planting contractors, but the lowest rooted wand survival (76.5%). The Hawke's Bay site had the

highest unrooted wand (98.5%) and rooted wand survival (93%). South-facing aspects had higher pole survival (98%) than north-facing aspects (92.3%), but lower unrooted and rooted wand survival (90% and 84.3% respectively) than north-facing slopes (91% and 89% respectively).

The results suggest there was no significant relationship between poplar deaths and morphometric or climatic variables. However, there was a statistically significant difference in growth rates between the north and south facing aspects, suggesting that microclimate may affect long-term survival. It was concluded that higher rainfall throughout the trial period potentially contributed to higher survival. Therefore, suggesting that in years of higher rainfall (i.e., East Coast during La Niña phases of the El Niño Southern Oscillation (ENSO) and positive Southern Annular Mode (SAM)), targeting planting in areas of higher non-survival risk should be completed to increase survival rates. Further research under more typical seasonal conditions is necessary to fully explore the morphometric or climate variable impacts.

This research has captured the opinions and knowledge of experienced industry practitioners which highlights the importance of several aligned variables that influence survival. It has provided a valuable systematic analysis of the cause of death of newly planted poplars and quantitatively assessed early establishment growth. These findings will be valuable to regional council planners, land management advisors and farmers and will potentially lead to more positive planting and reduced soil erosion outcomes for New Zealand hill country.

Acknowledgments

As with everything I've done in my life, this research would not have been possible without the love and support of many people.

Firstly, I would like to express my deepest gratitude to my supervisors; Dr Sam McColl whom I owe a great deal of my academic success to, who (to my great fortune) could be reached any time or day of the week over the past seven years. I thank him for teaching me another way to see the world; Dr Lucy Burkitt for always being an encouraging and steady guide when things felt a bit rocky, and for her unwavering support and dedication to her students and the New Zealand agriculture industry; and Dr Raphael Spiekermann for his patience in teaching me the intricacies of R and for providing so many laughs and good memories throughout our fieldwork together. I must thank Thomas Mackay-Smith for allowing me to watch his own research evolve and for being so pragmatic and practical in the face of adversity and Bob Toes for his experience, knowledge and unmatched morale during long days in the field. I would also like to thank Ian McIvor for sharing his wealth of knowledge and providing both personal and professional support. I am very grateful to have been surrounded by an amazing group of academics and good people.

This research would truly have not been possible without the financial support from the New Zealand Ministry of Business, Innovation and Employment research programme "Smarter Targeting of Erosion Control (STEC)". I would also like to thank David Boone and Tash Styles at Greater Wellington Regional Council for allowing me to continue completing this research while starting as a Land Management Advisor in their team.

I would like to thank the farmers who gave us access to their land for the planting trial. Richard and Becks Tosswill, Clem and Mickey Trotter, and Robbie and Ivanna Poole, thank you for the crucial role you all played in the completion of this research by limiting disruption caused by the global pandemic and for supporting the continued improvement of New Zealand's agriculture industry. I would also like to thank the regional council staff and industry scientists who contributed to the survey component of this research. They gave me generous amounts of their time to discuss the intricacies of poplar planting in hill country landscapes and I was blown away by their extensive experience and passion.

I owe everything to my family and friends who have supported me on this journey. To my friends, thank you for your patience and understanding. I will (metaphorically) throw my laptop out the window now, as promised. To my mum Leah, thank you for showing me the dedication of an ambitious woman, providing a safety net for me to follow my dreams and believing in my capabilities. To my older sister Jordana, I hope to be like you when I grow

up. Thank you for your friendship, patience, belief and understanding. To my younger sister Shya, thank you for dragging me out from behind my desk and back onto the netball court where I was able to come alive (and injured) again. To Susanna, thank you for being you and letting me be me. To my animals, Kody, Scout, Duke, and Moose. Who have kept me company throughout the lonely years of being a distance student and for always giving me a reason to go outside – of which I am eternally grateful. Lastly, to my husband Jason, thank you for bearing the full brunt of this labour. You have provided and cared for our family whilst watching what, undeniably at times would have looked like my own self destruction. Thank you for listening to my hours of rambling and enduring the rollercoaster it has been to get to this point. This research and my own personal growth could not exist without your support and sacrifice.

I would like to dedicate this thesis to my younger self, who had what it took to get here, although she didn't realise it at the time. I further dedicate this work to future generations of women entering the cross section of agriculture and environmental science. May you find a place worthy of your dedication and talent.

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Chapter 1
Introduction

1.0 Background

New Zealand has very active and dynamic landscapes (Blaschke et al., 2008). It has an inherent soil erosion risk due to its geologic-tectonic setting, mountainous topography, and its wet and stormy climate (Basher, 2013; Phillips et al., 2014). In addition to the naturally high erosion rates, extensive deforestation of indigenous vegetation during the 19th century to make way for pastoral agriculture has accelerated erosion (Phillips et al., 2014). Part of this acceleration has involved increased susceptibility to shallow, rainfall-triggered landslides, which deplete productive agricultural soil and increase sedimentation. Sedimentation has a detrimental effect on freshwater networks and loss of topsoil jeopardises the sustainability of hill country farming (Schwarz et al., 2016; Dymond et al., 2006). New Zealand pastoral systems established on steep hill country slopes (20-35°) are an example of a land use change which has had significant long-term adverse effects in terms of soil erosion (Schwarz et al., 2016; McCaskill, 1973). To help mitigate soil erosion, targeted conservation tree planting has been a widely utilised technique over the past 40 years in New Zealand pastoral hill country (Basher, 2013; Benavides et al., 2009; Douglas et al., 2009). Several planting systems have dominated: 1). Retirement of land for reversion to native forestry; 2). Plantation forestry (predominantly radiata pine); and 3). Wide-spaced planting of trees that enable continuation of livestock grazing.

Wide-spaced tree planting (space planting) is the planting system addressed in this thesis. The most common species utilised in space planting are poplars (*Populus*) and willows (*Salix*). Poplars were first introduced into New Zealand in the 1830s (Charlton et al., 2007). They were originally planted for several uses, including as shelter and amenity trees, for timber, and to mitigate riverbank and hill country erosion (Charlton et al., 2007). More recent varieties have been selected for improved features including non-brittleness, tolerances to drought, wind, wetness, and disease, and improved form (e.g., narrow crowning) (Charlton et al., 2007). Poplars are most widely used due to their easy vegetative propagation, their ease of establishment as large unrooted poles which can be driven into hill slopes, resistance to livestock, their superior early growth rates, flood and soil saturation tolerance, their extensive root systems, their ability to provide summer shade and shelter with less pasture suppression (due to their deciduous nature), and providing fodder for livestock (Mackay-Smith et al., 2021; Wilkinson, 1999; Hussain et al., 2009).

Despite the extensive use of space planted trees in pastoral systems, there has been little quantification of their effectiveness in reducing erosion at different scales (e.g., slope to farm and catchment scales) (Douglas et al., 2009; Spiekermann et al., 2021). Estimates for the effectiveness of space planted trees on soil conservation can vary greatly depending on the planting techniques used (Marden, 2012). For example, a study by Hicks (1991) suggested appropriately planted and maintained wide-spaced poplars could reduce soil erosion by 75% when compared to unplanted slopes under grazed pasture. This declined to a 10% reduction if trees were improperly planted (i.e., planted too far apart) and not maintained (i.e., no form pruning). An approach to assist planting planners has been proposed by Spiekermann et al. (2022a) using a multivariate statistical landslide susceptibility model. The model considers that the increase in slope stability due to the presence of trees (e.g., through root cohesion) is reduced with increasing distance from the tree trunk (Spiekermann et al., 2021). The model thus provides a spatially explicit approach to quantifying the effect of individual trees on slope stability at a range of scales, while controlling for other key variables such as rock type and slope gradient. In considering a selection of key determinants that influence slope instability, geospatial modelling can help inform where tree planting will be most effective at reducing future landslide erosion and sediment delivery to streams (Spiekermann et al., 2022b).

The relative effectiveness of soil erosion mitigation through tree planting is entirely dependent on successful tree growth (i.e., to establish roots, branches and leaves to provide mechanical and hydrological mechanisms to influence slope stability) and survival (i.e., remain as a living organism to maintain mechanisms to influence slope stability). It is suggested that space planted trees can reduce landsliding by a similar amount as close-canopy systems (70-90%) with the additional benefit of maintaining grazed pasture underneath, but only provided there is adequate tree establishment and survival (Basher, 2013). Successful establishment and survival can vary depending on the aforementioned variables that determine effectiveness. For example, landscapes susceptible to erosion often have shallow soils and are exposed to climatic extremes (e.g., high wind and rainfall exposure) (McIvor et al., 2011) and therefore are generally unfavourable for tree establishment and survival. These landscapes are often steep and have high runoff potential which can increase water-stress under normal rainfall conditions.

Information regarding poplar survival appears to be largely based on the experience of planners and planters in regional councils. Most information regarding poplar establishment and best practice is provided online and in the form of information brochures and videos with, in most cases, no reference to scientific literature. However, there has been some research on specific factors suggested to influence survival of trees planted for erosion

control. For example, Sulaiman et al. (2005) found that stem diameter (at time of planting) is a contributing factor to high survival, suggesting thicker stems had higher potential nutrient and carbohydrate reserves. Additionally, there appears to be minimal influence of planting depth, although greater planting depths do provide greater stability to the tree (Beaton, 1987). Cutting at the growth ring was found to encourage sprouting from the top of the poles and slant-cutting the base provides stability and prevents rotation of the pole in the ground if rubbed by livestock (Wilkinson, 1999). Despite these key findings relating to specific tree factors, there has been no research quantifying the comparative effects of these factors on tree survival. Where comparative effects have been addressed, they lack detail. For example, “the use of improved plastic protectors and more careful siting have improved survival rates from 40-60% in the 1960s to better than 95% on most sites in 1995” (Wilkinson, 1999). Two factors have been identified here, improved plastic protectors and more careful siting which have contributed to a 35-55% higher survival rate. However, it is not clear how much each factor individually influenced the higher survival rates or what specific factors were considered with ‘more careful siting’.

It is widely acknowledged throughout the available literature that soil water deficits are a major factor limiting survival of poplar trees in New Zealand (McIvor & Jones., 2015). A strong dependency on water availability is due to poplars’ high growth rates. An average poplar tree was found to use 180 L day^{-1} during spring (McIvor & Jones., 2015). When compared against 67 species (including hybrids), poplar water use was determined to be comparatively high (Guevara-Escobar et al., 2000; Mackay-Smith et al., 2021). However, there is a wide variability in the drought tolerance and water-use efficiency for different poplar species and hybrids (McIvor & Jones, 2015). The Veronese poplar clone is adapted specifically for its drought tolerant properties. Veronese (*P. deltoides x nigra*) is a black poplar hybrid imported from Italy (Charlton et al., 2007). It is naturally straight-stemmed and narrow-crowned which makes it a good option for wide-spaced plantings. Veronese have good drought and wind tolerance, but poor tolerance to rust disease and therefore perform well under drier East Coast region conditions (Charlton et al., 2007). Although drought tolerant, high survival of Veronese poplars has been found to be aided by high rainfall and soil moisture during establishment (i.e., August to March) (McIvor & Jones, 2015). Furthermore, based on survival modelling under current and future climates, pole survival is predicted to decrease in regions where increased susceptibility to prolonged drought is expected (McIvor & Jones, 2015).

Based on current knowledge, tree planting for erosion control in New Zealand is an effective method (Hancox & Wright, 2005; Dymond et al., 2006), but there is limited understanding of what is required to maximise the benefits of space planted tree systems. There is minimal

scientific evidence surrounding the specific factors influencing tree survival in order to ensure successful establishment will occur. Therefore, a gap has emerged for consolidation of current knowledge and additional scientific quantification of key factors influencing the survival of trees planted for erosion control in New Zealand hill country landscapes.

1.1 Research Aim and Objectives

The aim of this research is to provide a scientific basis for supporting planting decisions in erosion-susceptible hill country terrain in New Zealand to maximise survival of poplars planted for effective erosion control.

The specific objectives of this study are to:

1. Interview industry practitioners to determine what their practices involve and assess what influences their current practices of planting and establishing poplar poles for erosion control in New Zealand hill country.

2. Undertake a planting trial to quantitatively assess how different climate and topography conditions influence the survival and early growth of three plant material types of space planted poplars.

Chapter 2

Literature Review

2.0 Introduction

This chapter reviews the use of trees for biological control of erosion in New Zealand hill country, specifically poplars in silvopastoral systems and identifies the limitations in our current knowledge and therefore where the opportunities for future research lie. This information provides the background for the thesis research undertaken. Section 2.1 provides context regarding the history of erosion in New Zealand's hill country, erosion drivers and types, and the impacts of erosion. Section 2.2 details the tree mechanisms involved in soil conservation, focused on mechanical and hydrological mechanisms. Sections 2.3 and 2.4 review current knowledge of silvopastoral systems in New Zealand and tree survival research.

2.1 Erosion in hill country

Hill country is defined as all Land Use Capability (LUC) classes 5, 6 or 7 from the New Zealand Land Resource Inventory (NZLRI) with grade D slopes (i.e., slopes >15˚) located below an altitude of 1,000 masl (Jones et al., 2008; Basher et al., 2008). Under this definition, 10 million hectares (~37%) of New Zealand's total land area is classed as hill country (Basher et al., 2008). The majority (63%) is located in the North Island (Basher et al., 2008). The susceptibility of hill country landscapes to erosion is greatly influenced by geological, topographical, and climatic variables (Jones et al., 2008), for example in the East Coast region of the North Island, erosion is particularly severe due to the underlying weak rock. Due to inherently unstable slope conditions, mass movement is the most common form of hill country erosion in New Zealand, of which shallow landslides (soil-stripping landslides) are the most widespread (Jones et al., 2008). Gully erosion (mostly a fluvial process) is also very prevalent throughout New Zealand hill country, and sometimes gully and mass movement processes occur in the same locations and interact (Marden et al., 2018).

2.1.0 Soil Conservation History

New Zealand's soil conservation journey began with the clearing of native bush to pasture. This converted New Zealand soils from "a sponge to a slate" (McCaskill, 1973). The country saw drastic increases in soil erosion. Soil conservation efforts stepped up following the

Anzac Day floods of 1938 which caused devastating soil loss (e.g., the slopes surrounding the Napier-Wairoa Railway had approximately 11,500 cubic metres of slip debris come down (Cowie & Attwood, 1957)) and significant infrastructure damage. In 1939, a committee of inquiry was established, and published a report entitled 'Maintenance of Vegetative Cover in New Zealand, with Special Reference to Land Erosion'. The following year, the Minister for Agriculture called for direct action to be taken regarding erosion in New Zealand. This led to the enactment of the Soil Conservation and Rivers Control Act of 1941 which was the first time that the link between flooding and soil erosion was established in legislation. Under this act it was proposed to establish a central Soil Conservation and Rivers Control Council (SCRCC). Catchments around the country were managed by Catchment Boards (which are known today as Regional Councils). Despite this, flooding events continued to cause extensive damage. In the December 1993 and January 1994 floods near Gisborne, 0.66% of the surveyed area had landslides and, in some areas, up to 10% of total farm area had soil loss (McCaskill, 1973). Proposed solutions focused on river engineering works, which failed to consider the management of the catchment more broadly.

A wide-scale approach was presented alongside the development of the Land Capability Classification (LCC) handbook in 1939 in the United States. It was adapted and in 1969, the New Zealand version of the Land Use Capability (LUC) Survey Handbook was released (McCaskill, 1973). The LUC system was developed to help achieve sustainable land management practices at a farm-, catchment-, regional- and national-scale (Lynn et al., 2009). It works under two key components, the LUC Classification, and the Land Resource Inventory (LRI). The LRI is used for the LUC classes to determine sustainable productive uses for different areas. Land is categorised into eight classes (i.e., LUC Classifications) according to long-term capability of productive uses (Lyn et al., 2009) and the Land Resource Inventory (LRI) is an assessment of physical factors that are key for long-term land use and management. These factors include rock type, soil, slope angle, erosion type and severity, and vegetation cover. Erosion is a significant factor for sustainable land management (Lynn et al., 2009).

Sustainable land management practices within pastoral systems were further explored around the 1960s, with research showing the link between improved pastures (through improved species and fertiliser application) and more appropriate grazing management reducing soil loss and runoff volumes (McCaskill, 1973). This linkage gave farmers the confidence that soil conservation efforts could protect their soils and thus improve their productivity. Trees provided landowners additional options for managing and mitigating soil erosion (Section 2.2), but the effectiveness and benefits will depend on how the trees are used.

Erosion control schemes were developed during the 1960s and 1970s that focused on plantation forestry strategies (i.e., East Coast Project, East Coast Conservation Forestry Scheme) to mitigate the most erodible landscapes (Phillips & Marden, 2005). In 1988, Cyclone Bola presented a research opportunity following the extensive landslide damage across pastoral landscapes and in immature pine forests (<6 years) (Marden & Rowan, 1993). This evidenced the unsustainability of pastoral systems and young stands of pine forests during extreme rainfall events. Although landslides occurred under all vegetation cover, mature forestry experienced the least landslide damage (Marden & Rowan, 1993). A more recently recognised co-benefit of forestry has been the sequestering of carbon (C), reducing the accumulation of carbon dioxide (CO_2) in the atmosphere. Therefore, forestry has been included in the New Zealand Emissions Trading Scheme (NZ ETS). The ETS was introduced in 2008 to contribute to New Zealand's Kyoto Protocol obligations. Although the ETS was established to address emissions, it has incentivised afforestation which can also address erosion control. Under the ETS, a forest is defined as "an area of land of at least 1 hectare that contains forest species that have a crown cover of more than 30 percent on each hectare and an average crown width of at least 30 metres" (Karpas & Kerr, 2011). Although not impossible, this definition makes it hard for trees to be used effectively to target erosion control within pastoral systems without significantly reducing pasture growth.

2.1.1 Erosion drivers

The natural rates of erosion in New Zealand are high by international standards, as evidenced by our land making up ~0.1% of the global land mass yet discharging 1-2% of the global average annual sediment yields to the ocean (Jones et al., 2008; Hicks et al., 2011). New Zealand is characterised by high rainfall in the headwaters of most major catchments, high topographic relief, an abundance of erodible lithologies and soils, and susceptibility to earthquake shaking and high-intensity rainstorm events (Blaschke et al., 2008; Basher, 2013). These natural drivers are further exacerbated by anthropogenic factors such as deforestation, introduction of hard hooved grazing animals, soil management practices and unsuitable land use. The following reviews some of the key factors contributing to New Zealand's elevated erosion rates.

2.1.1.0 Geology and tectonics

New Zealand's main rock types are sedimentary in origin, comprising of sandstone and mudstone, which are highly erodible when poorly indurated (e.g., Neogene mudstones) and located throughout much of the North Island, or highly fractured (e.g., Greywacke) and comprise the majority of the mountain ranges (Wilkinson, 1999). Volcanic rock and the highly porous soils that develop throughout the Taupo Volcanic Zone in particular, are also highly

susceptible to erosion (Selby, 1972). Therefore, natural geological erosion rates are high throughout the country, but with variability due to local or regional differences in rock type and tectonic conditions (in addition to other factors such as topography, climate, and landcover). The highest rates of erosion outside of the Southern Alps are found in the East Coast forearc basin of the North Island, where the geology predisposes the landscape to high erosion. Tectonically uplifted, the elevated and incised topography of the upper catchments has steep slopes and experiences heavy rainfall that coincides with inherently unstable rock of Paleogene and Cretaceous age (Marden & Rowan, 1993). These rocks are clay-rich and fine-grained, and severely tectonically crushed. Consequently, they have extremely high susceptibility to weathering processes and erosion, exacerbated by high annual rainfall (2000-3800mm) (Marden & Rowan, 1993) maintaining the upper regolith in a perpetually wet state. Lower in the East Coast catchments, relatively less erodible steep hill country is underlain by Neogene sedimentary rocks that are less tectonically crushed, and often more competent. While still prone to instability, these rock types can support steeper valley slopes and erosion processes are typically confined to areas where the rock sequence is dominated by mudstone or bedding alignments are unfavourable (i.e., dip slopes). Hard rocks like greywacke, often found within the axial ranges, are still prone to erosion due to fracturing, steep slopes, and intense climate conditions, but are overall less susceptible to erosion compared to the younger, soft-rock terrains. This difference was notable in distribution of landslides in the Ruahine and Tararua ranges compared to the lower lying topography after the February 2004 Manawatū-Whanganui storm (Hancox & Wright, 2005; Dymond et al., 2006).

2.1.1.1 Role of topography and climate in erosion

The awareness and research into hill country erosion has been evidenced by main storm events throughout the 1900s (Basher, 2013). Notable events are Cyclone Bola in 1988 (Marden & Rowan, 1993) and the February 2004 Manawatū-Whanganui rainstorm (Hancox & Wright, 2005). Research into the effects of these storms has provided new understanding of erosion processes in hill country landscapes. For example, during the 2004 Manawatū floods, Hancox and Wright (2005) found that 56-86% landslide-affected slopes were in the strongly rolling to moderately steep class (16-25°). Northerly aspect slopes were more susceptible despite the prevailing wind (and therefore rainfall direction) during the event being from the south. It was determined that previous slope failures on the south-facing slopes reduced landslide susceptibility. Additionally, the north-facing slopes may have been more vulnerable to rainfall-induced landslides due to thicker, weaker, and more porous soils as a result of thermal weathering (Hancox & Wright, 2005). Landslide density between different parts of the affected region was influenced by terrain characteristics (i.e., slope

angle, slope height, and aspect) but more likely attributed to differences in rainfall intensities and amounts. Slope angle was determined to significantly effect landslide probability during the 15-16 February 2004 storm in the Manawatū-Whanganui region (Dymond et al., 2006). Similarly, in the Taranaki hill country (DeRose, 1996), the difference between erosion rates under pasture and forest increased with slope angle (Fig 1) (Basher, 2013).

Cyclone Bola was a short duration event (72 hours), which recorded rainfall totals of 917mm on the East Coast of the North Island with intensities of 23mm/h (Marden & Rowan, 1993); Marden and Rowan (1993) found that the greatest densities of landslides occurred on steep slopes with shallow soils. These observations suggest that erosion susceptibility varies spatially, and that mitigation efforts should be targeted to the most erodible (i.e., steepest) slopes. The research conducted by Dymond et al (2006) also noted an apparent difference in hillslope protection by different vegetation types under different slope angles. Greater slope angles in unconsolidated sandstone and mudstone had the highest probabilities of landsliding with non-woody vegetation (Figs 2 and 3). When different vegetation types were compared with slope angle and probability of landsliding, non-woody vegetation has significantly greater probability of landsliding compared to scrub, planted- and indigenous forests.

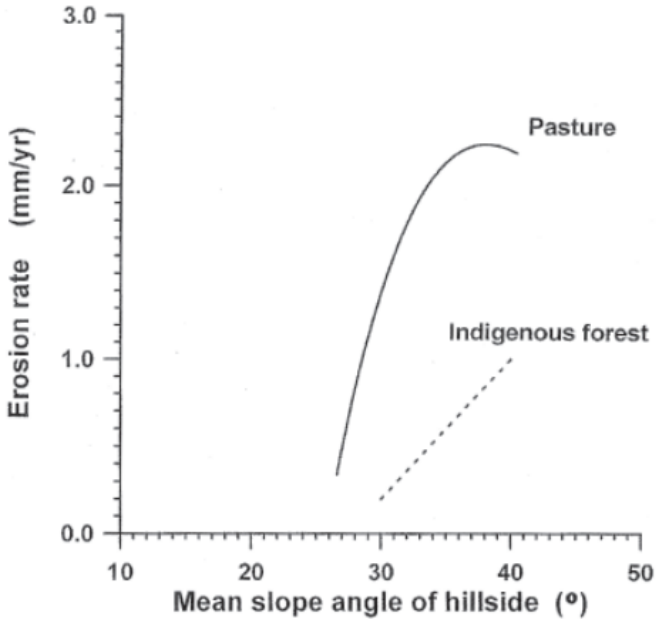

Fig 1: Relationship between increasing slope angle and vegetation cover on erosion rate (Basher, 2013).

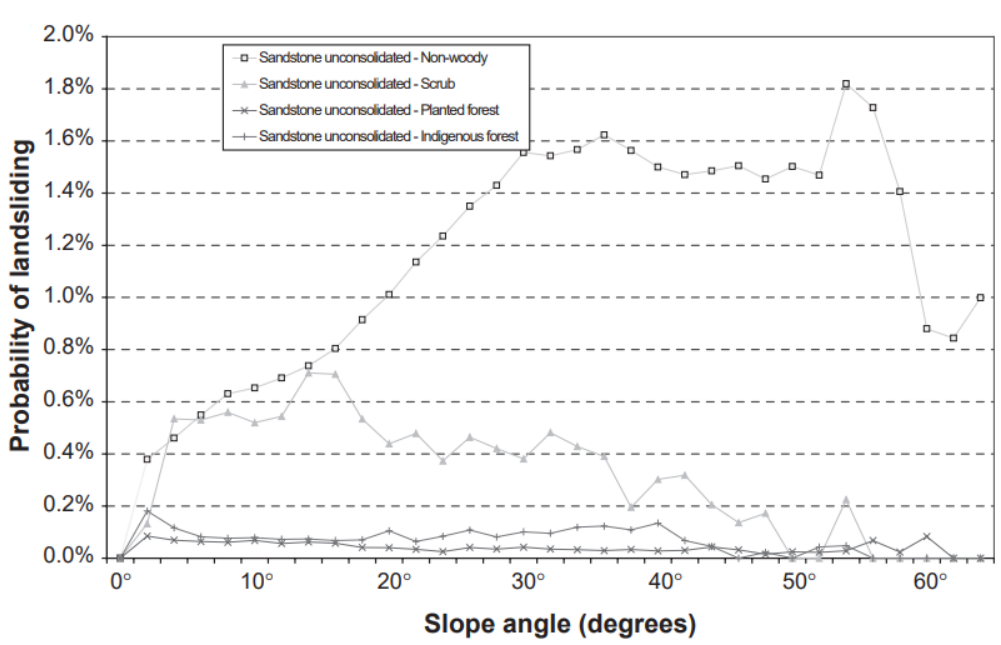

Fig 2: Landslide probability for unconsolidated sandstone in the Manawatū-Whanganui hill country landscape under different types of vegetation compared with slope angle. Landslide probability was calculated based on the proportion of land in an erosion scar (Dymond et al, 2006).

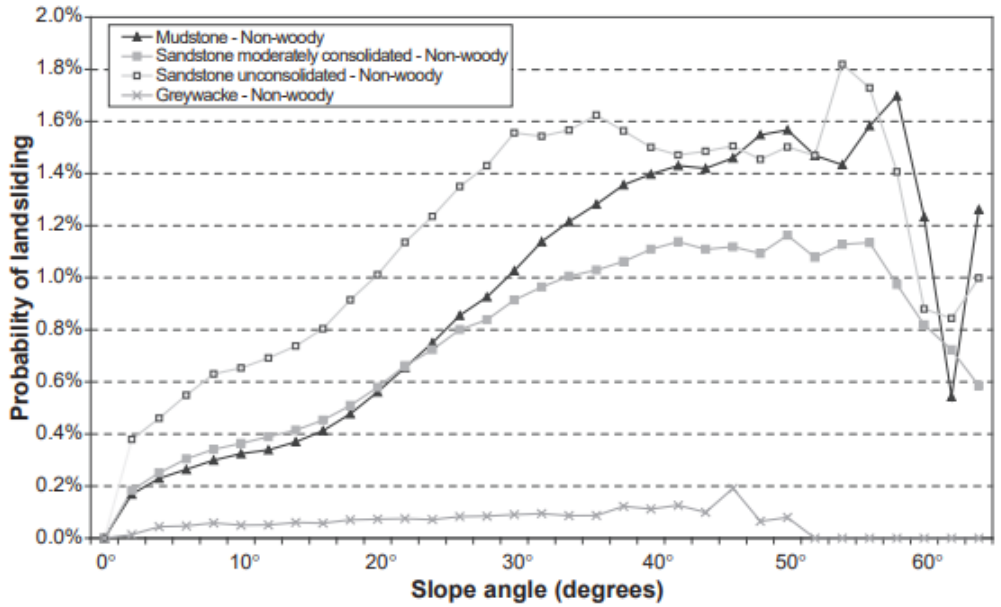

Fig 3: Landslide probability for the four main rock types in the Manawatū-Whanganui hill country landscape under non-woody vegetation compared with slope angle. Landslide probability was calculated based on the proportion of land in an erosion scar (Dymond et al, 2006).

2.1.1.2 Anthropic Factors

Drivers of erosion processes in New Zealand can be separated into pre- and post-human settlement. During the Holocene, sediment disturbances were related to climatic variability, volcanic activity (including erosion following forest fires initiated by volcanic activity, or in some cases lightning), earthquakes, and wind erosion (Glade, 2003). The natural order of

erosion processes was disturbed by the arrival of human settlements and subsequent deforestation. New Zealand's history of deforestation and its impacts have been widely documented (e.g., Jones et al., 2008; Basher et al., 2008: Kemp et al., 2018). Deforestation occurred in two phases: firstly, in the centuries following Māori settlement, ~50% of the forested area was removed, and secondly during the expansion of European settlement in the late nineteenth and early twentieth centuries where a further 30% of forest was cleared (Blaschke et al., 2008; Basher, 2013). The first phase was a significant change from New Zealand's undisturbed landscape; however, Māori were mostly active on flat landscapes (i.e., coastal regions, flood plains, and valley floors) thus increasing erosion on gentle slopes and degrading the soil, leaving hill slopes largely untouched and as a result, remaining stable (Glade, 2003). This situation changed significantly upon the arrival of European settlers which saw large proportions of New Zealand's hill country landscapes converted from forest to pasture for agricultural purposes (Glade, 2003).

2.1.2 Types of erosion in hill country

Mass movement is the most widespread type of erosion in New Zealand hill country (Basher, 2013), with shallow landslides dominating (Basher, 2013). Other widely distributed erosion types are sheet and rill erosion, and gully erosion. These main types of erosion have all used tree planting as potential mitigation (Hicks & Anthony, 2001).

2.1.2.0 Sheet and Rill erosion

Sheet erosion is widely distributed throughout New Zealand hill country and is a slow process, whereby millimetres of topsoil at a time are removed from parts of a slope during or after rainfall with the eroded sediment often deposited a short distance away (Hicks & Anthony, 2001). Sheet erosion typically occurs on areas of bare ground (e.g., forestry cutovers, cultivated slopes, farm tracks and erosion scars). Slope aspect, angle, length, soil type, and rainfall are influential factors for sheet erosion (Basher, 2013). Rill erosion is commonly associated with sheet erosion and has similar controlling factors (Basher, 2013). Rill erosion presents as small, long, narrow channels (i.e., 10 to 50cm) of topsoil removed by surface runoff. It is possible that repeated erosion of a rill develops into a gully (Hicks & Anthony, 2001). For both sheet and rill erosion, maintaining adequate ground cover ensures that the soil surface is protected from rainfall events. Control practices are more important on steeper landscapes (i.e., slopes of greater than 12°) where soils are loess or volcanic in origin, or sandy in nature (Hicks & Anthony, 2001).

2.1.2.1 Landslide erosion

Shallow mass movements such as landslides, can be categorised separately from deep-seated mass movements based on failure depth. Thus, a mass movement is shallow if it

occurs in the soil or regolith, and deep if it occurs in the underlying bedrock. Shallow landslide erosion is defined as the shallow and rapid sliding (or flowing) movement of the soil and subsoil of a slope, exposing a slip surface (Hicks & Anthony, 2001). This type of erosion is most evident during or immediately following heavy or prolonged rainfall (Hicks & Anthony, 2001; Basher, 2013). Heavy or prolonged rainfall saturates the soil, increasing the weight of the soil mass, lubricating the failure plane, and results in positive pore water pressure. This is the most widespread erosion in New Zealand hill country landscapes and can occur under all types of vegetation and on all terrains (Hicks & Anthony, 2001). Shallow mass movements can be further characterised into four forms common to New Zealand:

- Shallow landslides that strip soil or weathered regolith, typically occur on steeper slopes and which typically fail rapidly, triggered by rainfall or earthquake shaking.
- Earth flows are ductile, often slow-moving flows of soil or regolith, that can occur on low angle slopes and be triggered by prolonged wet periods.
- Debris avalanches are rapid flows of granular materials, usually sourced from steep mountain slopes, that may or may not involve water.
- Debris flows are rapid channelised flows of concentrated sediment and water (Hicks & Anthony, 2001).

Methods for reducing the risk of slip erosion include space planting trees (i.e., providing root reinforcement to soil), retirement and conversion into plantation forestry or reversion to native scrub (Hicks & Anthony, 2001).

2.1.2.2 Gully erosion

Gully erosion is described as the removal of soil by channelised runoff, forming distinct channels that are typically amphitheatre-shaped (Hicks & Anthony, 2001; Basher, 2013). Gully erosion is most common in the soft rock hill country of the East Coast North Island. There are several main forms of gully in New Zealand, including U-shaped, deep-seated, tunnel and mountain gullies.

U-shaped gully erosion

U-shaped gullies are widespread throughout New Zealand on soils which are susceptible to fluvial erosion (e.g., non-cohesive or uncompacted soils such as pumice, loess, alluvial sands, volcanic ash, and gravels). Additionally, it can develop where stormwater runoff is concentrated, and surface vegetation is in poor condition (Hicks & Anthony, 2001). Reducing peak flows within catchments can be achieved with vegetation. The practice of planting of the gully head (in small gullies only) or planting strong points at critical locations, have been suggested as principles of control (Hicks & Anthony, 2001).

Deep-seated gully erosion

Deep-seated gullies (i.e., V-shaped gullies) form where watercourses cut through surface regolith into unstable rock. They are most common in soft marine sediment, cemented marine sediment and crushed rock hill country where physical and chemical weathering processes determine severity (Hicks & Anthony, 2001). The main measures of control include stabilising the gully floor and the sides of the gully system and reducing the peak runoff throughout the system. Methods to stabilise the gully floor include the construction of debris dams. Stabilising the sides (i.e., increasing the shear strength) can be achieved through tree root reinforcement. A few planting options are available, including pole planting the toe of the gully slopes, planting the adjacent slopes with space planted trees, or afforestation of a reasonable proportion of the gully catchment (Hicks & Anthony, 2001).

Tunnel gully erosion

Tunnel gullies form by the concentrated flow of underground water above a less permeable soil layer. These concentrated flows form pipes which, upon widening can cause the roof to collapse forming a surface gully (Hicks & Anthony, 2001; Basher, 2013). This type of gully erosion can occur in a variety of lithologies where a variation in permeability in the soil profile occurs (i.e., when non-cohesive/soft lithologies overlay more resistant layers). Following tunnel gully collapse, normal gully erosion processes continue. Planting trees can be an effective tool for tunnel gully erosion. In slight to moderate situations, pole planting where the erosion feature has formed can help to stabilise the area. In more severe situations, diversion and control of overland flow is of greater importance and thus revegetation of dense, stable groundcover can be an option. Vegetation can also be effective in the case of space planting, and temporary or permanent retirement of affected areas (Hicks & Anthony, 2001). Tunnel gullies can form in mountainous settings, often found in the greywacke and schist mountains throughout New Zealand. They occur where runoff erodes debris avalanche scars and debris flow deposits. They are described as a natural phenomenon and almost impossible to control (Hicks & Anthony, 2001).

2.1.3 Impact of erosion on hill country agriculture

Erosion can have significant impacts on loss of productive agricultural land, damaging farm infrastructure (i.e., fences, sheds, tracks etc.) and reducing freshwater quality and freshwater ecology, thus requiring active mitigation methods to reduce impacts. Shallow landslides affect the greatest proportion of New Zealand hill country landscapes and, in combination with gully erosion, contribute the greatest, long-term, on-site (i.e., loss of topsoil and productive capacity) and off-site (i.e., flooding and sedimentation) environmental degradation (Basher et al., 2008). Additional on- and off-site effects can occur through landslide scars contributing to further erosion processes. These effects include loss of soil depth (and water

holding capacity), a loss of C, nitrogen (N), and nutrients (i.e., soil fertility), and reduced water quality of streams and rivers (Schwarz et al., 2016; Basher, 2013).

2.1.3.1 Farming systems

Several impacts of erosion result in reduced productivity of pastoral systems. For example, productivity on landslide scars after 20 years is 80% of that for undisturbed, stable sites that have been unaffected by landsliding (Basher et al., 2008; Schwarz et al., 2016; McIvor et al., 2011b). McIvor et al. (2011b) suggests that recovery beyond 80% is unlikely. This loss of pasture production is reflected in the loss of soil physical (i.e., soil depth, particle density) and chemical properties (i.e., total C, total N). For example, topsoil depths on eroded sites are approximately a third of topsoil depths on uneroded sites, affecting potential water storage capacity. The data is inconclusive whether surface total C can recover to uneroded states, however other soil properties (i.e., N, magnesium (Mg), sodium (Na), and cation exchange capacity (CEC)) are expected to recover within human time scales. The implications of these types of processes in areas of cumulative erosion (i.e., steep East Coast hill country with poorly consolidated parent materials) is the risk of progressive reductions in productivity resulting in areas that are unsustainable for agriculture over time, further increasing the risk of erosion.

2.1.3.2 Erosion impacts to waterways

Freshwater holds a range of environmental, cultural, social, and economic values to the people of New Zealand (*MfE & StatsNZ*, 2020). To ensure these values are upheld, there have been freshwater objectives built into government policies. Currently, New Zealand's freshwater management policy is undergoing changes. The Essential Freshwater package is part of a new national direction to improve and protect our freshwater systems and includes several new provisions including:

1. New National Environmental standards for freshwater.
2. New stock exclusion regulations.
3. The National Policy Statement for Freshwater Management 2020 (NPS-FM 2020) which replaces the NPS-FM 2017.
4. Amendments to the Resource Management Act (RMA) to provide a faster freshwater planning process and enable mandatory and enforceable freshwater farm plans with the creation of N fertiliser application caps for pastoral farms.
5. Amendments to the 2010 RMA regulations for measurement and reporting of water takes (MfE, 2020b).

National bottom lines for attributes requiring limits on resource use have been outlined (MfE, 2020c) and regional councils are required to set appropriate regional concentrations for

phosphorus (P) and N and monitor deposited sediment through engagement with communities and tangata whenua (MfE, 2020c). National targets could be problematic for regions of New Zealand that experience extreme sedimentation.

2.1.3.3 Sedimentation

Anthropogenic sediment in New Zealand's freshwaters is a by-product of predominantly agricultural practices (Ryan, 1991). An area that has struggled with this particularly is the East Coast region of the North Island which has received much attention in understanding and quantifying sediment load to waterways. Two rivers, the Waiapu and Waipaoa Rivers are estimated to deliver 35 Mt and 15 Mt per year of sediment to the ocean respectively (Hicks et al., 2011). This combined yield represents 42% of the total North Island sediment yield and 24% of the total yield to the New Zealand coast (Hicks et al., 2011). The impacts of sedimentation are reflected by the extensive damage the region has experienced during rainfall events. Specific impacts include flood severity, biological degradation, sediment accumulation and reduced water quality (Jones et al., 2008). Gully erosion in the headwaters of these catchments have been the primary erosion type contributing to this high sedimentation (Marden et al., 2008). Local mitigation strategies include afforestation, however, to achieve effective control in the larger gullies, a catchment approach is needed. It is suggested that it will take several decades for the beneficial effects of gully stabilisation (i.e., reduction in sediment yield) to be seen (Marden et al., 2008). Until then, it is likely that continued suppression of potential environmental co-benefits of reduced sediment yield by use of trees such as a reduction in channel aggradation or flood risk, improved water clarity and quality, or cost savings associated with repairs for flood damaged roads and bridges will be achieved (Marden et al., 2008).

2.1.3.4 Water quality

Erosion control is an integral component for the preservation of New Zealand's freshwater quality. The impacts of poor water quality include elevated concentrations of sediment, and diffuse pollutants (i.e., nutrients such as N and P), and faecal microbes from runoff and leaching (Doehring et al., 2020). One of the main issues with determining the best land management practices to achieve improved water quality or ecosystem health is the timeframes used to monitor changes (Doehring et al., 2020). Doehring et al. (2020) suggests a minimum of ten years to detect changes in water quality parameters, including nitrate concentrations and water temperature.

An indicator of water quality is the densities of invertebrate's present (Ryan, 1991) and turbidity is the strongest determinant for reduced invertebrate density and biomass. The effects that increased turbidity has on invertebrate communities can range from interference

with feeding through to death through smothering (Ryan, 1991). High suspended sediment can also alter fish populations for similar reasons, but most importantly by the direct impacts of food chain related effects (Ryan, 1991). Aside from ecological considerations, aesthetic effects of suspended sediment are important. Clear water is more acceptable for water consumption and recreation (Ryan, 1991). Limiting and monitoring concentrations of N and P is required for water quality under the NPS-FM 2020 (MfE, 2020c). Both nutrients are necessary for all plant and algal growth. However, in excess, P and N can contribute to problematic growth of macrophytes (i.e., rooted plants) and periphyton (i.e., slime) and phytoplankton (i.e., algae) which can all impact ecosystem health (MfE, 2020a; MfE, 2020d). Higher concentrations of excess N can lead to indirect toxic impacts on aquatic animals resulting in limited growth and in some cases mortality (MfE, 2020d). High nitrate in water used for drinking (i.e., ground water) can also lead to blue baby syndrome in babies.

2.2 Tree mechanisms involved in soil conservation

It is recognised that even under forest regimes, landsliding can still occur and be the dominant erosion process (Glade, 2003). This reminds us that vegetative cover won't eliminate erosion, but it may significantly reduce it. Indeed, multiple studies have quantitatively demonstrated the influence of trees in mitigating erosion, particularly when compared with areas under pasture (e.g., Marden & Rowan, 1993; Marden, 2004; Jones et al., 2008; Hicks, 1990; Pain & Stephens, 1990; Dymond et al., 2006). Hicks (1991) examined a transect through the East Coast hill country after a major storm (Cyclone Bola) and found that pasture had eight times more landslides than forested land (i.e., indigenous or exotic). Marden and Rowan (1993) examined nine study sites and found that pasture had sixteen times more landslides than forested land and four times more than scrub. Pain and Stephens (1990) examined five study sites and found that 10% of pasture was covered in landslides, whereas less than 1% of forested land and scrub was covered in landslides. The variability of these results reflects either site-specific processes due to the limited area of study sites, or the combined influence of factors other than vegetation (Dymond et al., 2006).

A closed-canopy indigenous or evergreen forest is suggested to provide the best stabilising method for erosion processes (Marden, 2012). The influence of closed-canopy vegetation can be profoundly effective in reducing landsliding by 70-90%. (e.g., Hancox & Wright, 2005; Dymond et al., 2006; Marden & Rowan, 1993; Basher, 2013). However, closed-canopy vegetation (i.e., forestry) is not conducive to pasture growth and therefore productive grazing systems. If it is desirable to maintain grazing systems on hill country, then space-planted trees can be used to help mitigate erosion.

It is difficult to assess which planting system and species is most effective in mitigating erosion due to the overall lack of direct comparative research with consideration of contributing variables. For example, a study that partially assessed the comparative influence of vegetation cover after the event of Cyclone Bola, in the East Coast of the North Island was completed by Marden and Rowan (1993). They found that landslide density was highest in areas of pasture and exotic pines <6 years of age. However, the analysis of planting systems was incomplete as the effects on space-planted systems were not included. There has since been research completed that shows the effects of space-planted trees (Section 2.3). Potential contributing variables could include erosion potential and type, climate, land use, and site characteristics including aspect, soil type, soil depth, and moisture content. On less susceptible landscapes where pastoral systems are the continued intended land use, poplars planted from 3-m poles is common practice. Poplars have been successful in pastoral systems due to their ease of establishment from poles in the presence of livestock. Vegetative erosion control through pole planting has proven successful, however, in the most susceptible landscapes (i.e., active mass movements such as earthflows or slumps, and gully erosion) their success is limited. Space-planted poles can provide protection against shallow landslide initiation if planted in appropriate positions on slopes and at sufficient densities (Basher et al., 2008) see Section 2.3.1.

2.2.1 Hydrological effects

The main hydrological effects afforded by trees is modifying the soil moisture regime through evapotranspiration which reduces soil pore water pressure, and volume and rate of stormwater runoff (Hicks & Anthony, 2001; Stokes et al., 2009). Additionally, in gully catchments, trees modify and decrease peak runoff in rainfall events (Hicks & Anthony, 2001). However, shallow landslides typically occur during autumn and winter rain events when soils are nearly saturated, and evapotranspiration is low. Therefore, the effects of modifying the soil moisture regime can be minimal (Stokes et al., 2009; Sidle & Ochiai, 2006) and it is under dried conditions where evapotranspiration may reduce the potential for shallow landslides to occur. The effects of evapotranspiration on landslide occurrence can result from the following:

1. Interception of rainfall and snow by canopies of vegetation, thus promoting evapotranspiration and reducing water available for infiltration
2. Root systems extract water from the soil for physiological purposes (via transpiration), leading to lower soil moisture levels
3. Roots, stems, and organic litter increase ground surface roughness and soil infiltration capacity (Sidle & Ochiai, 2006).

The first two points are the most important meaning that different vegetation types and covers will determine their effectiveness (Sidle & Ochiai, 2006).

2.2.2 Mechanical effects

The contribution of soil shear strength provided by tree roots is considered more important in stabilising hillslopes from landslide erosion in comparison to hydrological effects (Sidle & Ochiai, 2006). The more significant effects of trees on the stability of a slope are due to the addition of soil strength and cohesion properties attributed to rooting systems (Stokes et al., 2009). Rooting systems have the potential to penetrate the entire soil mantle in shallow soils, thus anchoring the soil into more stable substrate. Additionally, lateral roots form a stabilising membrane in the upper soil horizons and large roots can provide reinforcement across potential slope failures (Stokes et al., 2009). Shallow landslides can be greatly influenced by such mechanisms; however, deep-seated landslides are minimally benefitted due to lower root densities reducing with depth, such that few or no large roots may reach beyond the basal failure plane (Stokes et al., 2009). The effectiveness of erosion protection of trees is influenced by species, age, growth rate and planting densities. The (adverse or beneficial) mechanical effects on landslide occurrence can result from the following:

1. Individual strong woody roots anchor the lower soil mantle into the more stable substrate
2. Strong roots tie across planes of weakness along the flanks of potential landslides
3. Roots provide a membrane of reinforcement to the soil mantle, increasing soil shear strength
4. Roots of woody vegetation anchor into firm strata, providing support to the upslope soil mantle through buttressing and arching
5. Weight of trees (surcharge) increases the normal and downhill force components
6. Wind transmits dynamic forces to the soil mantle via the tree bole
   (Sidle & Ochiai, 2006).

Hydrological and mechanical mechanisms can be seen in Table 1 which indicates the influence on shallow landslides and deep-seated mass movements and indicates whether the mechanism is adverse or beneficial. This further illustrates the complexity of assessing afforestation for slope stability.

Table 1: Influence of hydrological and mechanical mechanisms of woody vegetation on slope stability (Sidle & Ochiai (2006) used with permission).

Mechanisms	Influences on types of landslides: Shallow, rapid	Influences on types of landslides: Deep-seated
Hydrological mechanisms	B	B
1. Interception of rainfall and snow by canopies of vegetation, thus promoting evaporation and reducing water available for infiltration	B	B
2. Root systems extract water from the soil for physiological purposes (via transpiration), leading to lower soil moisture levels	MA	MA
3. Roots, stems, and organic litter increase ground surface roughness and soil's infiltration capacity	MA	MA
4. Depletion of soil moisture may cause desiccation cracks, resulting in higher infiltration capacity and short-circuiting of infiltrating water to a deeper failure plane		
Mechanical mechanisms		
5. Individual strong woody root anchor the lower soil mantle into the more stable substrate	B	MB
6. Strong roots tie across planes of weakness along the flanks of potential landslides	B	B
7. Roots provide a membrane of reinforcement to the soil mantle, increasing soil shear strength	B	B
8. Roots of woody vegetation anchor into firm strata, providing support to the upslope soil mantle through buttressing and arching	B	MB
9. Weight of trees (surcharge) increases the normal and downhill force components	MA/MB	MA/MB
10. Wind transmits dynamic forces to the soil mantle via the tree bole	A	MA

A = mechanism adverse to stability; MA = marginally adverse mechanisms; MB = marginally beneficial mechanisms; B = beneficial mechanisms.

2.3 Silvopastoral systems in NZ

Silvopastoral systems optimise complex interactions between livestock, trees and pasture and have stabilised erodible hill country in New Zealand for over 40 years (Benavides et al., 2009; Douglas et al., 2009). The presence of trees reduces light and water reaching pasture but may also reduce adverse climatic conditions such as high wind speeds and extreme temperatures. During tree establishment, negligible effects on pasture are seen. However, as tree age increases, Benavides et al., (2009) measured a decline in pasture production and nutritive value under shade. However, a recent study has shown that pasture soils under spaced kānuka had improved soil conditions including greater porosity, organic matter, and cation exchange capacity (CEC), in addition to significantly greater composition of species indicative of good pasture condition (Mackay-Smith et al., 2022b). This study found that pasture production increased by 107.9% under spaced kānuka compared to open pasture (Mackay-Smith et al., 2022a).

The extinction point of pasture has been found to occur at 85% canopy closure for deciduous trees (*Populus*) compared to 67% for evergreen trees (*Pinus radiata*) (Benavides et al., 2009). This is mainly attributed to the leafless period of deciduous trees that enables pasture recovery and their litter has relatively fast decomposition rates which reduce the effects of smothering pasture. New Zealand silvopastoral systems typically include one or

more of the genera, *Acacia*, *Eucalyptus*, *Pinus*, *Populus*, and *Salix* (Douglas et al., 2009). Poplars (*Populus*) remain the most common choice of tree for New Zealand silvopastoral systems and have attracted the most attention in the erosion literature, and consequently is the focus of this research.

2.3.1 Poplar use in New Zealand

Poplars (*Populus* spp) were planted extensively (>2 million planted) during the 1960s and 1970s in erosion control schemes, but later declined due to the increased emphasis towards P. radiata (pine) forestry as a soil erosion control measure (Wilkinson, 1999). Poplar planting gained renewed interest in the 90's alongside Willows (*Salix* spp), due to their suitability to establish in the presence of livestock (with adequate protection) on pastoral hill country soils susceptible to landslides (Benavides et al., 2009; McIvor et al., 2011b; Mead, 1995; Wilkinson, 1999). Poplars have thrived in this role, due to their ease and rapid establishment, tolerance to wet soil conditions and flooding, extensive root systems, provision of shade and shelter (in summer) and supplementary feed for livestock (McIvor et al., 2011b; Wilkinson, 1999; Kemp et al., 2018; McIvor et al., 2020; Benavides et al., 2009; Schwarz et al., 2016). Poplars are usually established using 3-m poles (vegetative cuttings), encased in a protective sleeve, and planted directly into soil. Typical tree spacings of 10-15 m are common, but spacings are influenced by the risk or potential for erosion and the advice and experience of the planting practitioner (Schwarz et al., 2016).

The use of space planted poplars across susceptible slopes and at higher densities in gullies has been supported and encouraged by varying government agencies since the 1960's (Kemp et al., 2018; Wilkinson, 1999). Generally, a range of planting densities for poplar of 25-256 sph have been recommended (McIvor et al., 2011b). However, there is limited research regarding long-term root development and the root densities that different planting densities achieve. Work completed by McIvor et al. (2005) concluded that for trees of 9-11 years of age, the ideal planting density for erosion control with adequate pasture production is approximately 84 to 770 sph. Douglas et al. (2010) suggested that densities of 160, 210, and 237 sph provided moderate to high root occupancy of soil layers. Therefore, these densities could be recommended for enhancing soil strength while enabling varying degrees of pasture production. Although recognised as best practice for sustainable pastoral farming on erosion susceptible landscapes, the profitability of poplar silvopastoral systems within erosion prone areas is debated due to the difficulty in valuing long term soil stability on hill slopes (Kemp et al., 2018).

2.3.1.0 Poplar erosion control research

Few studies have quantified the soil stabilisation effects of space planted poplars. Hawley and Dymond (1988) estimated the average radial influence of poplars on the occurrence of landslides in Gisborne. An average of 8.4m^2 of soil was estimated to be protected from failure and this decreased pasture production losses by 13.8%. Building on this work, Hawley (1988) determined the influence of root encroachment from neighbouring trees. A reduction of landsliding around an individual tree from 8.2% to 1.4% was estimated when considering the contribution of a neighbouring tree planted at a spacing of 11.5m (i.e., 75 sph stems per hectare). Hicks (1995) suggested that mature poplars at a spacing of 12m (i.e., 70 sph) can reduce mass movement in pasture by 50-80%. However, Basher et al. (2008) estimated a 34% reduction in erosion by spaced trees compared with open pasture during the 15-16 February 2004 Manawatū-Rangitikei storm based on the data presented in an extensive vegetation survey by Hicks and Crippen (2004). Douglas et al. (2009) quantified the effectiveness of space planted trees and found that in slopes of approximately 27°, the reduction of soil slippage was on average 95% when compared with open pasture sites.

2.3.1.1 Advantages and disadvantages of poplars

Poplar trees' overarching benefit is to provide a method of erosion control for hill country pastoral landscapes in the presence of stock through the establishment of large unrooted poles, but they convey other benefits and advantages over alternative species. They are deciduous and therefore provide shelter and shade for animals from spring to autumn and due to shedding their leaves in winter, are less likely to suppress pasture growth throughout the entire year (Hicks & Anthony, 2001). There is now a wide range of poplar clone varieties available in New Zealand with superior characteristics (Table 2) and improved growth and form (Wilkinson, 1999). Furthermore, their leaves are edible, so can be managed as a coppice and browsed silvopastoral system, whereby tree height and density are optimised for livestock browsing to provide supplementary feed during summer drought (Kemp et al., 2018).

2.3.1.1.1 Clones

New Zealand’s hill country environments vary from subtropical to cool temperate at the northern and southern ends of the country respectively. Furthermore, there is a preference for drought-tolerant clones in the eastern regions and rust resistant clones in the western regions with respect to rainfall patterns (McIvor et al., 2011a). The coastal regions require salt tolerant clones and often experience high winds. The advantage of having access to a variety of poplar clones means that the right clone can be selected for specific situations.

The main clones grown by nurseries and regional councils include Argyle, Kawa, Tasman, Toa, and Veronese (Charlton et al., 2007). The below table shows the recommended poplar clone varieties for various site characteristics or desired products in addition to erosion control benefits.

Table 2: Poplar clone varieties commonly used in New Zealand based on tolerances and intended purposes outlined in Charlton et al. (2007).

Tolerances/Purpose	Variety
Drought resistance	Veronese, Tasman, Argyle, Dudley, Fraser, Selwyn, Crowsnest, Yunnanensis
Wet, sheltered valleys and moist areas	Eridano, Kawa, Toa, Otahuao, Weraiti
Windy, exposed slopes	Veronese, Crowsnest, Fraser, Selwyn, Tasman
Fodder	Flevo, Tasman, Veronese, Argyle
Timber	Kawa, Veronese, Yeogi, Weraiti, Otahuao
Firewood	Kawa, Yeogi

The following information is a current observation on poplar clone use in New Zealand from one of the countries most experienced poplar researchers (I. R. McIvor (Senior Scientist at Plant & Food Research and General Manager and Lead Scientist of The New Zealand Poplar & Willow Research Trust), personal communication, September 23, 2022). It is estimated that Veronese, Crowsnest, and Kawa clones account for over 70% of the poles planted nationally. It is acknowledged that some regions throughout New Zealand have access to more clones because they have nurseries. Some general trends include:

- Higher numbers of Shinsei in the western districts of the Horizons region
- Weraiti, Otahuao, and Fraser are planting throughout the Hawke's Bay and Greater Wellington regions
- High numbers of Kawa planted in Waikato due to high growth of Kawa in local nurseries
- Northland and Taranaki plant small numbers of a wide range of clones, including the newer *maximowiczii x nigra* and *deltoides x ciliate* clones
- Canterbury also has a wide range of clones, however supply numbers are low
- There is almost no Toa or Argyle sold nationally now

2.3.1.1.2 Pasture production

In New Zealand, the amount of pasture produced in silvopastoral systems is largely determined by the planting density and thus the level of tree canopy shade (Kemp et al.,

2018). To optimise pasture production in silvopastoral systems, trees need to be pruned, coppiced, or thinned as they grow. The botanical composition and nutritive value of pasture in silvopastoral systems has been reported to be broadly similar to that of open pasture systems. However, metabolic energy (ME) values reduce slightly during peak shade in summer, but recover after leaf fall (Kemp et al., 2018).

Trees have been found to alter the local environment and thus influence the microclimate. This is most notably achieved through effects of light, water, wind, temperature, macronutrients (including N and C) and micro-organisms. Trees have been reported to influence the quality and quantity of light reaching the understorey pasture. This reduction in light affects the physiological processes of plants and decreases pasture carbohydrate manufacturing and net production of dry matter (Benavides et al., 2009). Dry matter can be reduced by soil water deficits, mainly through limiting leaf area development. Soil water deficits can occur by reduced rainfall through interception and to a lesser extent, evapotranspiration. Trees also influence wind and temperature by providing a physical barrier. This can be beneficial in terms of wind protection which reduces physical damage to plants. Temperature is an important factor for pasture production (due to its effects on physiological processes such as photosynthesis, respiration, and germination) and shade for soil and air temperature due to its physical barrier of wind and incident radiance (Benavides et al., 2009). This is seasonally influential.

Tree presence can influence pasture production through altering nutrient levels and soil biodiversity. It is suggested by Wall (2006) that *Populus* can be used for bioremediation for controlling soil acidification as the pH of soil beneath *Populus* has been found to be higher than in open pastures (Wall, 2006). N has a fundamental role as a plant nutrient and combined with C are major constitutes of plant and soil organic matter. It has been shown there is an increase in C and N mineralisation under trees when compared with open pastures, particularly near the surface (Benavides et al., 2008). This may be contributed to by higher organic matter (leaf litter and dead roots) and the modified environmental conditions beneath trees (i.e., temperature). Other macronutrient increases under trees have been previously measured, for example Guevara-Escobar et al. (2002) found under mature *Populus* (<29 years), concentrations of calcium (Ca), potassium (K), magnesium (Mg), and sodium (Na) (kg ha^{-1}) were 41, 116, 64, and 21% higher respectively, compared to adjacent open pastures. Additionally, Singh et al. (1989) found higher soil concentrations of N, P, and K with respective increments of 19, 65, and 55% were found in *Populus* stands compared with *Eucalyptus* hybrids. Higher concentrations of invertebrates in soil under trees have been reported. Research by Park et al. (1994) found that in a *Populus* silvoarable system (spaced at 14 m x 3 m) 1.5-2.5 times more invertebrates were located within 1 m of the trunk

compared to the soil under crops. It was suggested that the soil beneath trees improved soil properties through contributing more organic matter and modifying the microclimate.

2.3.1.1.3 Poplar management

There is an increasing awareness of the need for ongoing management of poplars planted for erosion control (McIvor et al., 2011b). There are adverse effects for unmanaged trees as they age, including increased susceptibility to limb breakage and toppling. This can cause damage to farm infrastructure (e.g., building, fences, tracks etc.), injure humans or livestock, and create debris that can require greater workload to the landowner. To avoid these impacts, the practice of pollarding (i.e., removing the entire canopy) has been advocated (McIvor et al., 2011b). This practice prevents large trees from developing and can provide supplementary fodder for livestock during feed deficits. The suitability of this practice is greatly determined by the access to the trees and if they can be managed safely. The effects of pollarding on root distribution are still being explored but it is suggested that the density of managed poplars will need to increase to achieve similar erosion control effectiveness, compared to unmanaged trees (McIvor et al., 2005).

2.3.1.2 Potential economic and environmental considerations

In New Zealand, poplars are not used as forestry trees and therefore cannot be directly compared economically with plantation forestry (e.g., radiata pine). However, the economic benefits of poplars could be valuable when considering the impacts of high erosion risk, animal welfare and production, whether regional council subsidies are available for reducing erosion and C sequestration. If economic return for forestry is the most important farm output, then forestry systems of radiata pine is likely to be the most viable solution. However, if livestock enterprises are the primary output, then targeted space planting of poplars may be an economically viable option (Benavides et al., 2009). C sequestration has received recent attention leading to opportunities for poplars to be included within the ETS. The full eligibility requirements (briefly mentioned in section 2.1.0) for entering poplar plantings under the ETS requires meeting the ETS forest land definition, thus a stand of trees must:

- Occupy more than 1 hectare
- Be capable of reaching 30% canopy cover
- Be a tree species capable of growing taller than 5-m, on that site
- Be capable of reaching a width of at least 30-m on average
- Be on Post-1989 forest land
  (*Forest360*, 2019).

Research was undertaken focusing on the potential for C sequestration on floodplain land owned by Environment Southland (Paul, 2021). The results showed the following estimated

rates of C sequestration from different stocking rates of poplars based on two different models over a 30-year period (Table 3). However, these estimates could be hindered by the effects of pollarding or toppling. However, within the context of ETS eligibility, the disadvantage of a stand achieving at least 30% canopy cover is there is an estimated reduction in pasture production to 75% of that of open pasture (Wall, 2006).

Table 3: Two different approaches for estimated carbon sequestration rates and carbon stocks over a period of 30 years for different stocking rates (stems/ha) (Paul, 2021)

	Mean total annual sequestration rate ($tC02e/ha^{-1}/yr^{-1}$)	**Total carbon stocks at age 30 years (tC02e/ ha-1)**	**Approach**
Poplar at 37 stems/ha	2	42.2	Guevara-Escobar et al. (2002) described in Burrows et al. (2018)
Poplar at 200 stems/ha	10.8	228.1	
Poplar modelled at 40 stems/ha	6.6	198	McElwee and Knowles (1998) & Beets (2006)
Poplar modelled at 200 stems/ha	9.9	299.9	

2.4 Survival

Recent research has shown how modern technologies allow the influence of individual established trees to be evaluated (Spiekermann et al., 2022), but little research has been done to evaluate the establishment and survival of individual trees. Although previous research has detailed the importance of mechanical influences (i.e., root cohesion) on influencing slope stability, there has been limited data on the effects of root distribution of young poplars on slope stabilisation specifically (McIvor et al., 2008; McIvor et al., 2009). It is suggested that it may take up to 5 years for poplar trees (established from 3-m poles) to develop a root network that will effectively bind soil (McIvor et al., 2008). Regardless, existing measures of the effectiveness of trees planted for erosion control are based almost entirely on the assumption that a planted tree will survive and grow to maturity. Although poplars are known for successful establishment, quantitative research on establishment and the factors that influence survival are relatively sparse.

2.4.1 Qualitative Literature

Reference to generalised factors for poplar survival has been described throughout the literature but are often not quantitatively measured. Suggested survival factors for tree

establishment and effective erosion control include planting method and site selection (i.e., nutrient requirements, climate, competition, pests and diseases and protection) (NZFFA, 2005; Satchell & Marden, 2018). Planting methods greatly determine the future root system of the tree. Common mistakes include not planting deep enough, not creating a big enough hole to accommodate the root system (if rooted cuttings are used) or not appropriately compacting soil around the base of poles (NZFFA, 2005; Marden & Phillips, 2013). Site selection is also key and requires careful considerations in terms of nutrient requirements, climatic conditions, and geographical location (NZFFA, 2005; Satchell & Marden, 2018). Some species and clones are better suited to warmer or cooler climates with higher or lower rainfall, or more prone to unsuccessful establishment through drought, frosts, or high winds (Satchell & Marden, 2018). The location of the site will also determine the ability to plant species that are susceptible to environments such as coastal sites, or sites at higher altitudes (NZFFA, 2005; Satchell & Marden, 2018). In general, survival rates should increase with adequate protection from stock, competition, including other vegetation, and pests and diseases (NZFFA, 2005; Satchell & Marden, 2018). The available qualitative information illustrates the complexity of a range of influential variables, making it difficult to identify key factors that will determine poplar survival success.

2.4.2 Quantitative Literature

Some New Zealand studies have quantified the survival rates of poplars relative to a small selection of variables. Sulaiman et al. (2005) compared the survival rates of the poplar clone 'Veronese' in relation to planting depth and stem diameter. Results showed that survival ranged from 91 to 100%, and the influence of stem diameter was significant (survival rates for diameters of 10mm, 25mm, and 35mm were 93, 99, and 98% respectively) (Sulaiman et al., 2005). Research was conducted to determine the influence on pole survival and early growth from the addition of N or P fertilisers at planting (McIvor et al., 2018) for trees that were planted across the same soil type and slope. It was hypothesised that fertiliser would result in an increase in survival. The survival of the four treatments ranged from 80 to 100%, with the study concluding these differences were insignificant. It was suggested that the mortality was rather influenced by position on the slope, as 71.43% of the deaths occurred close together in what was described as a drier microsite (McIvor et al., 2018).

Although survival may occur alongside considerable above-ground biomass in the first year, trees can die in subsequent years from desiccation, or the effects of poor planting technique, poor root development, drought conditions, or narrow pole diameter (McIvor et al., 2020). According to McIvor et al (2020), during the first three years following planting, root development in more compacted soils (sandy or clay loam) was lesser than for less compact

soils (pumice). This could lead to delayed deaths amongst a poplar stand. For example, a pilot study was undertaken focusing on the survival and growth of poplar and willow pole planting on East Coast hill country in 2009 (Marden & Phillips, 2013). The results showed that after planting (in 2009), 74% (198 trees) of the poplar poles had survived 24 months after planting, decreasing to 60% (160 trees) a further 21 months later. Stock damage accounted for 9% of poplar pole losses within 24 months and increased to 12% within 24 months. Site factors considered as contributing to pole mortality included socketing (i.e., movement of a pole creating an air gap between the base of the pole and the surrounding soil), and a combination of slumping and bank undercutting along gullies and drainage channels. Socketing can result in poles unable to access the nutrient resources provided by the soil horizon or exposing roots to the air and possible pests and diseases, causing dieback. The site factors contributed to 17% of losses for poplars within 24 months and increased to 28% within 45 months. Based on the estimated pole losses for the 2004-2007 plantings and the actual pole losses for the 2009-2012 plantings, the author described the results consistent with those from other sites, showing small initial losses of poles following establishment (i.e., 1 year after planting), but increasingly greater losses in subsequent years when the majority of the poles had become well established.

The available quantitative research focuses on a single, or small number of variables to determine poor survival rates. This does not encompass the complexity of successful establishment or provide evidence to reduce the range of suggested variables that may impact survival. The current quantitative research creates a lack of clear and generic guidelines or well-established principles for planting poplars to increase survival.

2.4.3 Research gaps

Much of the knowledge surrounding poplar survival factors appears to be based on practitioner experience or on few quantitative studies within a relatively dynamic system. Additionally, there appears to be a range of opinions amongst tree planters in New Zealand of the factors influencing survival. Within current knowledge and experience throughout the country, there is a need for evidenced-based and consistent planting practices to maximise survival of trees on the erosion prone slopes where they are most needed. Therefore, an opportunity exists that this information could be consolidated to provide a resource that enables knowledge sharing that may not otherwise occur. This knowledge is important and holds weight, however, there is a gap for further quantitative research into survival factors that ideally would be considered during the planning phase of planting. One of the key factors identified by previous research, and present within the existing literature is the adequate practice of siting and choice of planting position on the selected slope, but this

factor has not been robustly tested. Multiple variables could contribute to the effect of slope position. For example, aspect, slope gradient and curvature, wind exposition, topographic position index (TPI) and topographic wetness index (TWI). It would be beneficial to examine how these variables influence survival of a combination of qualitative and quantitative data to determine key survival factors for poplars planted for erosion control in New Zealand's hill country landscapes.

2.5 Conclusion

Poplar's space planted in hill country landscapes for soil conservation purposes have been common practice in New Zealand for decades. Previous research has shown that space planted poplars can reduce landslide erosion, deeming them a popular choice when utilised in a pastoral system. However, the magnitude of landslide reduction is based on the survival of poplar trees planted. This review provides an explanation for why trees are successful in New Zealand's hill country for promoting soil conservation and highlights the important factors that influence the choice of poplar use in New Zealand, including their ease of establishment, the ability to be grown in the presence of stock, and their erosion mitigating properties. Additionally, this review has highlighted the relative abundance of information based on experience and opinion surrounding poplar survival, compared to the relative lack of quantitative poplar survival literature. These findings suggest that successful plant establishment on landslide susceptible landscapes is predominantly determined by site selection considerations including water accessibility, and management practices including stock exclusion. If adequate pole quality and commonly utilised planting techniques are used, there are a variety of morphometric and climatic variables that may be influential. Thus, there is a need for consolidation of current survival knowledge and further quantitative assessment of potential survival factors. This will provide the basis for providing informative survival advice for poplar-pastoral systems.

Chapter 3 Research Methods

3.1 Introduction

To evaluate the factors contributing to poplar survival and early establishment in hill country landscapes, two main studies were undertaken. The first study involved semi-structured interviews with personnel from key agencies involved in hill country tree planting in New Zealand. The interviews followed a series of survey questions aimed at capturing key information about planting decisions and knowledge of tree survival. The second study was an experimental poplar establishment trial, to quantitatively evaluate how climatic and topographic variables influence tree establishment and survival.

3.2 Study 1: Semi-structured interviews

A semi-structured interview was conducted with tree planting practitioners and scientists to explore the key concepts and knowledge surrounding the survival of trees planted for erosion mitigation. This qualitative research approach was used to help understand an issue (survival) that appears to be poorly documented or formally captured by existing literature. Knowledge and views held by practitioners can also provide insights that could guide future research in this space. A low-risk ethics approval was given for this research.

Regional and district councils were identified as institutions that could provide key perspectives due to their decades of accumulated institutional knowledge on planting poplars (particularly within the respective trial site regions of Study 2) and experience in planting practices. Three regional councils and one district council were selected: Greater Wellington Regional Council (GWRC), Hawke's Bay Regional Council (HBRC), Horizons Regional Council (HRC) and Gisborne District Council (GDC). The councils coincide with the tree-planting trial locations (Study 2, Section 3.3), and all have active council tree planting programmes for soil erosion mitigation. Additional knowledge was sought from the Poplar and Willow Trust and Plant and Food Research to provide a national perspective and contribute a research-based outlook.

Initial contact was established with these institutions through email. It was decided by each institution how many and which staff would participate. Three participants spoke on behalf of GDC, one from each of the three regional councils, and one senior scientist spoke on behalf of the Poplar and Willow Trust and Plant and Food Research. Interviews were audio recorded to enable data to be reviewed at a later date (O'Leary, 2017), and all participants gave informed consent for this to occur. Interviews were conducted between May and

August 2022 and were transcribed verbatim. Key ideas and themes were identified and presented in this thesis. It is important to acknowledge the potential for the researcher's perspective and relative position to shape the research. The following statement enables the reader to consider the researcher's position related to the research undertaken.

"When I started this research, my background was in agriculture. I have lived and worked on sheep and beef stations along the East Coast of the North Island for the past 7 years. This has given me incredible insights into the agriculture industry, and I have grown a great fondness for the rural community of New Zealand. During my undergraduate studies, I supplemented my core agriculture courses with environmental science and physical geography elective papers. In doing so, I realised the importance of the relationship between agriculture and environmental outcomes. This inspired me to complete postgraduate studies focused on more advanced environmental science and physical geography courses, strengthening my understanding of the issues within the agriculture sector. This interest was my primary motivation for undertaking a Master of Science degree. This connection to the rural sector and experience within science-based education could present bias in my interpretation of results collected from the interviews with industry practitioners."

The interview posed eight questions (Appendix A) designed to identify key factors that influence survival in trees planted for erosion control for the participants' respective regions, and their experience and opinion on poplar planting effectiveness for erosion control. There were several questions aimed at determining the practices used by regional councils throughout the planning and planting process, to provide an understanding of similarities and differences between regions. A semi-structured survey approach was used in all interviews, which combined the structure of a series of questions to be covered, with the freedom to follow up with questions when necessary (e.g., if an interviewee's response needed clarification; Thomas, 2009).

3.3 Study 2: Tree establishment trial

3.3.0 Site selection

The tree survival experiments were conducted at three North Island hill country farms, which were chosen to target different climate regimes. Two were low rainfall sites east of the North Islands axial range, with one cooler southern site (Gladstone in the Wairarapa region) and one warmer northern site (Ahuriri, in the Hawke's Bay region). The third site was a higher rainfall site west of the axial range (Taumarunui in the Manawatū-Whanganui region) (Fig 4). Two hillslopes were selected at each farm with assumed contrasting microclimate based on their opposing hillslope aspect. One had a predominately north-facing aspect (potentially a summer dry stress site) and the other had a predominately south-facing aspect (potentially a winter wet stress site). The hillslopes each had terrain with high susceptibility to shallow landslide erosion.

Fig 4: North Island map showing the three trial sites (created by T Mackay-Smith)

3.3.1 Selection of slopes within each farm

Upon obtaining farmer permission to establish trial sites on their properties, a site visit was conducted on each farm to identify slopes with high landslide susceptibility (i.e., that could benefit from tree planting to improve hillslope stability). Site selection was guided by maps of landslide susceptibility (Figs 5, 7, and 9; Smith et al., 2021; Spiekermann et al., 2022), and evidence of previous slope instability in the form of landslide scars or deposits present on the target slopes or on similar adjacent slopes. Potential northern and southern aspect sites were indicated on the maps, and these were shown to landowners and land management advisors to determine areas that would ideally meet the aspect specifications within areas classed as highly susceptible to landslide erosion that aligned with their management practices. Additionally, good accessibility helped guide the selection of suitable sites.

3.3.2 Climate data

Climate is considered to be an important variable to affect the survival of poplars (McIvor et al., 2011; McIvor & Jones, 2015). Rainfall and its effects on soil water deficits is suggested to

be the most important climatic factor due to the rapid establishment of poplars and their high dependency on water availability (Sulaiman et al., 2005; McIvor & Jones, 2015). To confirm the assumption that we had chosen sites with contrasting climates, the decadal rainfall patterns at each site were analysed using daily rainfall totals from the nearest NIWA weather stations. Data were downloaded from the NIWA CliFlo database, across a 22-year period (2000 – 2022; Table 4). These data were also used to evaluate the seasonal patterns in rainfall between each site, and to evaluate whether the trial took place under 'normal' climate conditions (i.e., typical for that region). The rainfall data were presented graphically to show the seasonal variation (daily rainfall), and deviation in the long-term rainfall patterns. Deviation in the long-term pattern (showing the relative wetness or dryness across the entire 22-year period) was calculated as the cumulative deviation from the mean daily rainfall over the 22-year period. Additionally, daily rainfall was presented graphically for a 3-year period prior to and inclusive of the trial period. The 3-year period aimed to show the trial period in more detail, outlining the summer months and how the immediate years preceding the trial period may have been influential on potential groundwater reserves. Graphs were also presented using data from on-site climate monitoring stations (Section 3.4.2) showing several climatic variables including rainfall (mm), temperature (°C) and solar radiation (W/m^2) compared between both aspect slopes at the Taumarunui and Hawke's Bay sites. The Wairarapa site was excluded due to the rainfall data collection issues caused by a technical breakdown of the on-site climate monitoring stations.

Table 4: NIWA CliFlo stations used to compare rainfall patterns and totals for all trial sites

Location	Agent number	NIWA climate station elevation (m)	Trial site elevation (m)		Distance from site (km)
			North-facing aspect	South-facing aspect	
Wairarapa	2613	111	300	300	4.1
Hawke's Bay	2980	3	48	116	6.4
Taumarunui	2264	457	333	328	12.8

3.3.3 Detailed site characteristics

3.3.3.1 Eastern Wairarapa (Gladstone)

3.3.3.1.1 Location and topography (Physiography)

Te Awa Awa Farm is located 15 km east of Masterton in the Wairarapa (175.74° E, 41.05° S, 300 masl). The north and south aspect sites are located on opposing sides of the same gully (Fig 5). The site has old landslide scars, particularly on the southern aspect (Fig 6). The

average slope gradient is 10.8° and 13.8° for the north and south aspect, respectively. For each study area, the average slope gradient was calculated by averaging the slope gradients, calculated from a 15-m DEM, at each GPS-located tree. The area has been described as steeply dissected by streams with extensive areas of soil slip erosion underlain by unconsolidated, tectonically deformed Tertiary siltstone (Rosser & Ross, 2011; Lambert et al., 1984).

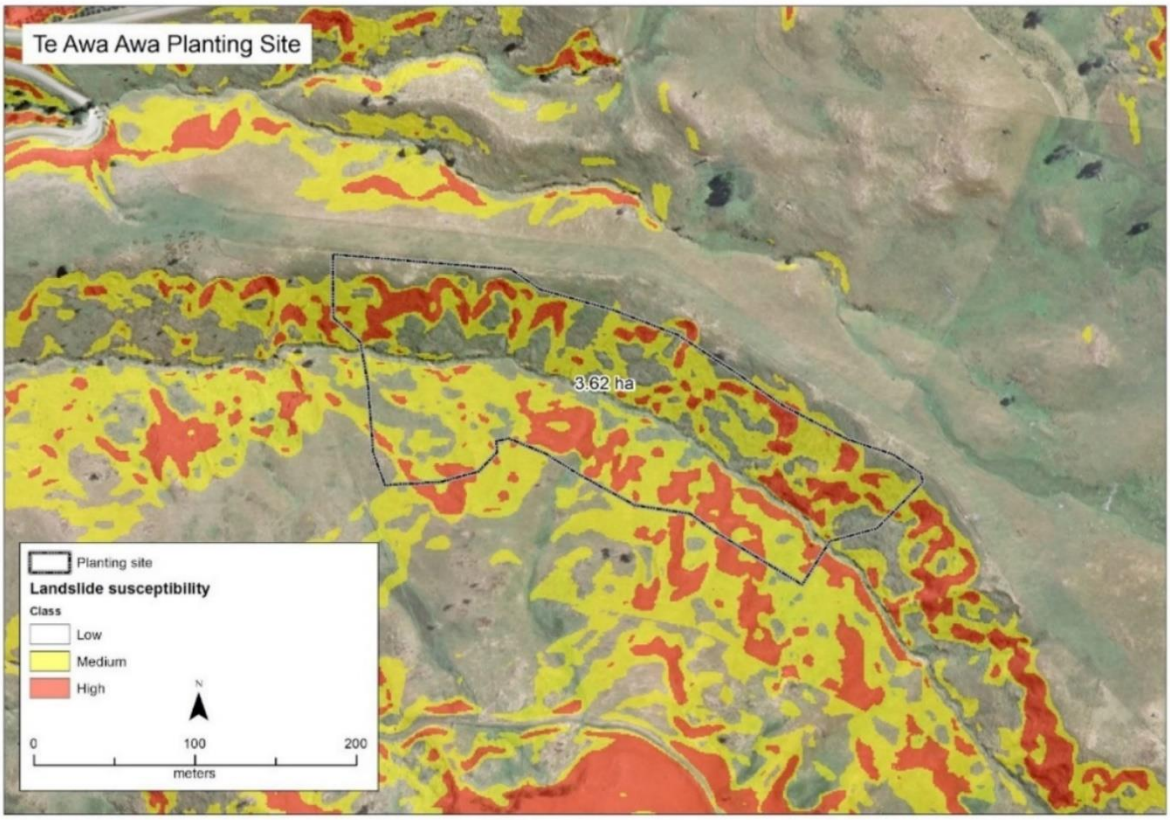

Fig 5: Gladstone, Wairarapa site map indicating high landslide (High LS) susceptibility on northern and southern aspects (Cartography by R. Spiekermann)

Fig 6: Wairarapa site showing the north-facing aspect (left side of photo) and south-facing aspect (right side of photo)

3.3.3.1.2 Climate and soils

The eastern hill country of the Wairarapa is typically described as summer dry (i.e., low rainfall in summer months) and regularly experiences summer drought conditions (Rosser & Ross, 2011). Both the northern and southern slopes at Wairarapa are made up of Gley and Brown soils (Table 5) according to available S-Map data. S-map data are indicative only, and the soil classifications were not field-truthed as part of this thesis. Gley soils are located throughout New Zealand, forming in landscapes where prolonged wetness has resulted in oxygen depletion (Hewitt & Dymond, 2013). They often occur in low parts of the landscape where there are high ground water tables, or in places where there is greater water accumulation, such as at the base of slopes, in sloping gullies or seepages (Hewitt & Dymond, 2013). Gley soils are typically found in high rainfall areas and can represent the original extent of wetlands (Hewitt & Dymond, 2013). Gley soils are described as poorly or very poorly drained, and rooting depths may be limited by depleted oxygen below the water table (Hewitt & Dymond, 2013). Therefore, the saturated conditions and low oxygen content can be problematic for plant establishment and growth. Trees that are adapted to tolerate saturated conditions often prevail. The Brown Soil order is the most extensive within New Zealand, occurring mainly on hill country in the lower North and South Island (Hewitt & Dymond, 2013). The name ‘Pallic’ refers to the pale colouring of the subsoil due to their low

contents of iron oxides (Hewitt & Dymond, 2013). Orthic Brown Soils lack the firm subsoil layers and other than fertility requirements, have fewer productive limitations (Hewitt & Dymond, 2013). Brown Soils typically have good infiltration capacity; however, infiltration capacity and profile permeability vary depending on the nature of the parent material (Hewitt & Dymond, 2013). Root exploration of the soil is generally good in these soils.

Table 5: Soils for the Te Awa Awa sites at Gladstone, Wairarapa. Data sourced from S-Map database with a medium confidence level.

Soil Name	Estimated Area within Site (%)	Soil Classification	Profile texture	Structural Vulnerability	Aeration in Root Zone	Drainage class	Rooting barrier
Waitataura_14a.1	60	Pallic Orthic Brown Soils	Silt	Moderate (0.57)	Moderately limited	Moderately well drained	Fractured rock
Taihape_10a.1	40	Typic Orthic Gley Soils	Silt	High (0.64)	Very limited	Poorly drained	Pan

3.3.3.2 Hawke's Bay (Ahuriri)

3.3.3.2.1 Location and topography (Physiography)

Brooklands Station is located in the Puketapu district, approximately 8 km north-west of Napier in Hawke's Bay The north and south aspect sites (Figs 7 and 8) are located 1.7 km apart (176.791° E, 39.479° S, 48 masl for the north-facing aspect site, and 176.779° E, 39.475° S, 116 masl for the south-facing aspect site). The average slope angle is 20.7° and 19.2° for the north and south aspect, respectively. The Hawke's Bay region has a varied landscape, it lies on the eastern side of the Ruahine and Kaweka Ranges and includes hill country, flat plains, and coastal landscapes (Pollock, 2009). The farm itself is predominantly hill country, with flats suitable for cropping at the front of the property.

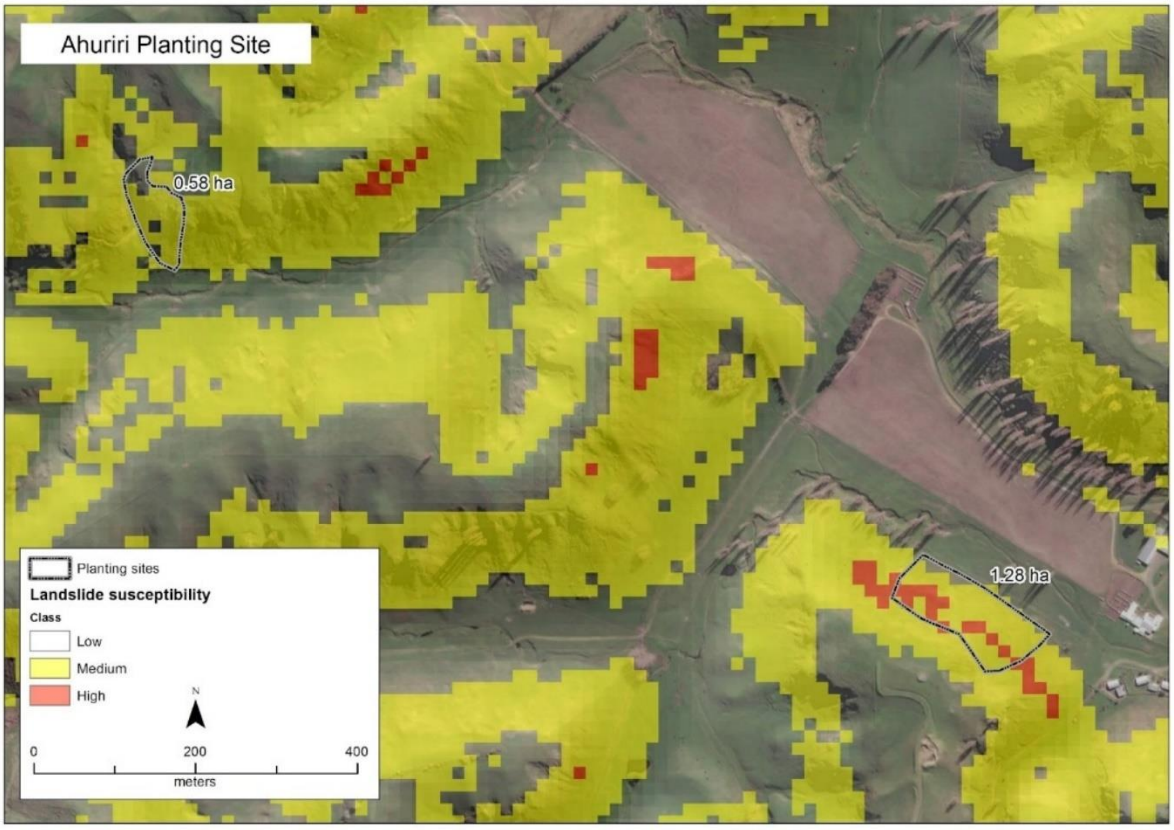

Fig 7: Ahuriri, Hawke's Bay site map indicating high landslide susceptibility on northern and southern aspects (Cartography by R. Spiekermann)

Fig 8: Hawke's Bay north-facing site (left side of photo) and south-facing site (right side of photo)

3.3.3.2.2 Climate and soils

The Hawke's Bay is typically described as summer dry and regularly experiences summer drought conditions however, rainfall can be highly variable (Pollock, 2009). At both the Northern and Southern sites at Hawkes Bay are Pallic Orthic Brown Soils (which are described in Section 3.3.3.1.2), and Pallic Soils (Table 6) based on S-Map data. Pallic Soils are prominent in the lower North Island and are the third most extensive soil order throughout New Zealand (Hewitt & Dymond, 2013). They occur in regions which are typically

summer dry and commonly have a dense fragipan in the subsoil which can obstruct drainage and root penetration and therefore result in pugging in winter wet conditions. Pallic soils have weak structure and high density. However, Immature Pallic Soils have no fragipan or argillic horizon with weakly expressed Pallic Soil features (Hewitt & Dymond, 2013). Therefore, there is a higher versatility, which enables a deeper rooting penetration and higher available water capacity (Hewitt & Dymond, 2013). The term pedal describes a soil that when in a moist state, has some or all the soil material in the form of peds (Houghton & Charman, 1986). Peds are individual, natural soil aggregates. Pedal soils could be described as well aggregated and therefore important for water holding capacity, exchanging of gases (e.g., oxygen), minimising the risk of compact waterlogging and thus erosion. Mottling describes the presence of more than one colour in the same soil horizon (Houghton & Charman, 1986). This is typically an indication of slow internal drainage but can also be reflective of the weathering of certain parent materials. It was confirmed by a HBRC Catchment Management Lead that the description of 'Oaklea_9a.1' was reasonable for this farm.

Table 6: Soils for the Brooklands sites at Ahuriri, Hawke's Bay. Data sourced from S-Map database with a low confidence level.

Soil Name	Estimated Area within Site (%)	Soil Classification	Profile texture	Structural Vulnerability	Aeration in Root Zone	Drainage class	Rooting barrier
Porewa_4a.1	20	Pallic Orthic Brown Soils	Silt	High (0.62)	Unlimited	Moderately well drained	Fractured rock
Airedale_1a.1	25	Pedal Immature Pallic Soils	Silt	Moderate (0.59)	Moderately limited	Well drained	Massive rock
Oaklea_9a.1	55	Mottled-pedal Immature Pallic Soils	Loam	High (0.67)	Moderately limited	Imperfectly drained	No significant barrier within 1m

3.3.3.3 Taumarunui

3.3.3.3.1 Location and topography (Physiography)

Pooles Manunui Block is located approximately 2 km south-east of Taumarunui in the Manawatū-Whanganui region (Fig 9). The north and south aspect sites are located 0.64 km apart (north-facing: 175.281° E, 38.904°, 333 masl; south-facing: 175.281 E, 38.897 S, 328 masl). The average slope angle is 22.9° and 23.9° for the north and south aspect, respectively. The farm consists of moderate to steep hill country.

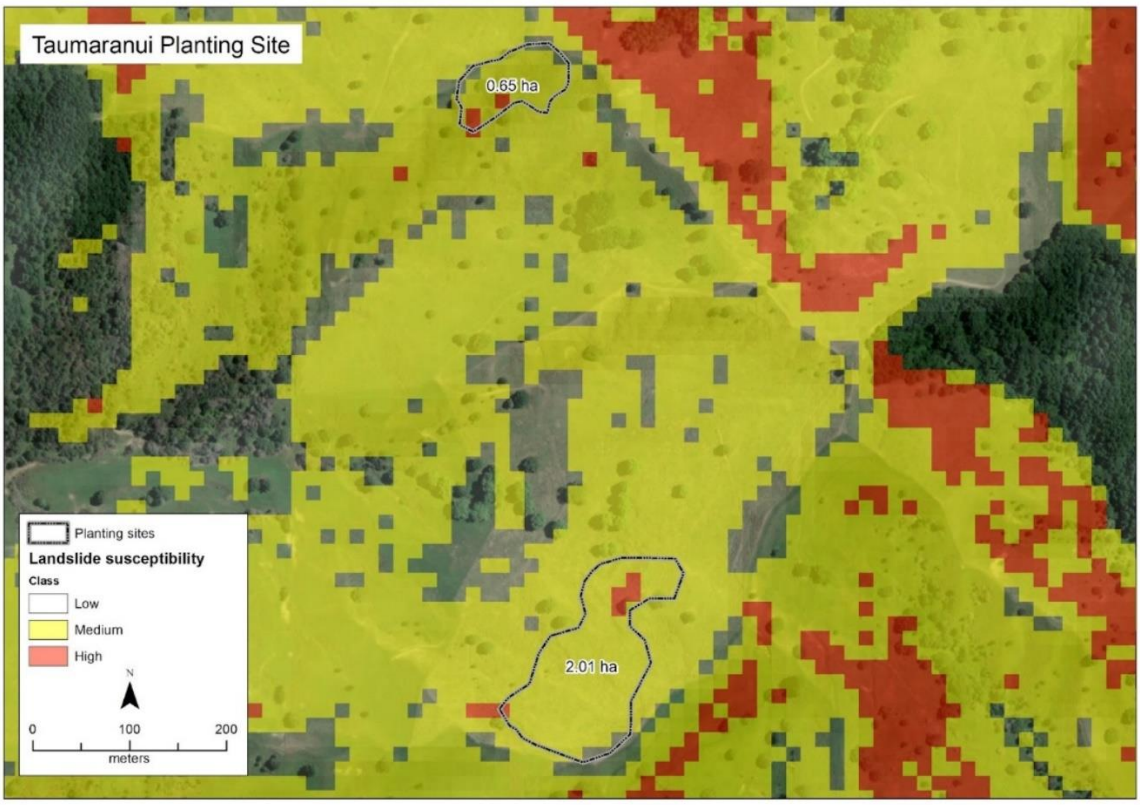

Fig 9: Taumarunui site map indicating high landslide susceptibility on northern and southern aspects and two selected planting sites (Cartography by R. Spiekermann)

3.3.3.3.2 Climate and soils

Taumarunui is typically considered as summer safe (i.e., high rainfall during summer months). At the northern site at Taumarunui, there is a dominance of Typic Orthic Recent Soils (Table 7) based on S-Map data. Recent soils develop where material has been eroded or deposited and soil development has occurred on new parent material (Hewitt & Dymond, 2013). Soil development is sufficient to form a topsoil, but a B horizon is either absent or weakly expressed. Their occurrence is not determined by climate, or parent materials but rather the presence of young landscapes such as alluvial floodplains and unstable hill country (Hewitt & Dymond, 2013). Orthic recent soils are found most commonly on eroded hillslopes. At the southern site at Taumarunui, Pallic Orthic Brown Soils are present and have been described in section (Section 3.3.3.2.2). Additionally, Typical Orthic Allophanic Soils are found (Table 8). Allophanic soils are typically formed in accumulations of tephra (volcanic ash) in areas of higher rainfall with relatively good drainage (Hewitt & Dymond, 2013). These soil's physical properties are excellent for supporting plant growth. They are generally well drained but also have high soil-water retention. Plant roots are able to move readily through the soil with little resistance.

Table 7: Soils for the Northern Taumarunui site. Data sourced from S-Map database with a low confidence level.

Soil Name	Estimated Area within Site (%)	Soil Classification	Profile texture	Structural Vulnerability	Aeration in Root Zone	Drainage class	Rooting barrier
Mahoenui_6a.1	100	Typic Orthic Recent Soils	Loam	High (0.67)	Slightly limited	Well drained	Massive rock

Table 8: Soils for the Southern Taumarunui site. Data sourced from S-Map database with a low confidence level.

Soil Name	Estimated Area within Site (%)	Soil Classification	Profile texture	Structural Vulnerability	Aeration in Root Zone	Drainage class	Rooting barrier
Waitataura_7a.1	40	Pallic Orthic Brown Soils	Silt	Moderate (0.54)	Moderately limited	Well drained	Massive rock
Otorohanga_33a.3	60	Typic Orthic Allophanic Soils	Loam	Very low (0.31)	Unlimited	Well drained	No significant barrier within 1m

HRC resources showed at the Taumarunui site, the north-facing aspect has Typic Orthic Brown soil (BOT) and General Orthic Typic soil (GOT). BOT are well drained sedimentary mudstone soils. They are typically found on moderately steep slopes with medium treading damage and risk of erosion. Slope is considered the most limiting factor. GOT are similar to BOT soils but with the presence of some gleying in the topsoil and throughout the layers. They are present on moderate to steep slopes and less well structured to BOT soils. Therefore, they are poorly drained and susceptible to pugging. The south-facing aspect is similar with the addition of Typic Orthic Allophanic soil (LOT). LOT is a well-drained ash soil that is found on rolling slopes. It has a strongly developed topsoil and is susceptible to compaction (W. Brown, personal communication, December 12, 2022).

3.4 Experimental treatments and design

3.4.1 Plantings

Ninety trees were planted on each hillslope aspect at each farm. Thirty of the following trees: 3-m poplar poles, 2-year poplar wands, and 1-year poplar rooted stock (Fig 10) were planted at a spacing of approximately 5-m and at different heights up the slope. Wands and rooted stock were included to assess whether they could provide an alternative to poles, which take longer to prepare in the nursery, therefore helping to address shortages in 3-m poplar pole supply. The trees were planted in July 2021 at the Wairarapa and Hawke's Bay sites and later in the year (October 2021) at the Taumarunui site due to the Covid-19 travel restrictions. Planting was carried out by the Research Team (including Massey University staff and students, researchers from Manaaki Whenua and Plant and Food Research) and

respective Regional Council staff. Poles and wands were supplied by the farm's respective regional councils and unrooted wands were supplied by a farmer in Elsthorpe, Hawke's Bay. Veronese was the predominately used clone, however, different planting stock clones (Shinsei and Kawa) were used at Taumarunui due to a shortage of Veronese poles and wands at the Taumarunui nursery. Pole bars were the most commonly used implement for planting of 3-m poles; whereas planting by spade was the only technique used for unrooted and rooted wands. The planting specifications for each site is presented in Table 9. Protection against animal damage was installed at every tree (Fig 11). Commonly used Dynex sleeves were installed on all 3-m poles, and cages were installed on all wand and rooted stock. For the cages, a batten was hammered into the uphill side of the tree, and a stainless-steel cage was placed over the tree with several staples used to secure it to the batten. A variety of cattle exclusion practices were utilised based on the farmers capacity/preference. All cattle were excluded from the Hawke's Bay sites, adult cattle were excluded from the Wairarapa sites (i.e., yearlings and weaners had access to trial site paddock) and no cattle were excluded from the Taumarunui sites. Farmers reported that there were no issues with feral animals at any of the sites.

Fig 10: Plant types used in the trial, rooted wands (left), unrooted wands (middle), 3-metre poles (right)

Table 9: Planting specifications across all trial sites

Location	Pole Type	Planting			
		Clone	**Technique**	**Planters**	**Protection**
Wairarapa	Pole	Veronese	Pole bar	GWRC contractors	1.7m Dynex sleeves
	Wand	Veronese	Spade	Research team	Stainless steel tree guards (1700mm x 1200mm)
	Rooted	Veronese	Spade	Research team	Stainless steel tree guards (1700mm x 1200mm)
Hawke's Bay	Pole	Veronese	Auger and pole bar	HBRC LMAs	1.7m Dynex sleeves
	Wand	Veronese	Spade	Research team	Stainless steel tree guards (1700mm x 1200mm)
	Rooted	Veronese	Spade	Research team	Stainless steel tree guards (1700mm x 1200mm)
Taumarunui	Pole	Shinsei	Borer/ Auger and pole bar	Horizons LMAs	1.7m Dynex sleeves
	Wand	Kawa	Spade	Research team	Stainless steel tree guards (1700mm x 1200mm)
	Rooted	Veronese	Spade	Research team	Stainless steel tree guards (1700mm x 1200mm)

Fig 11: Protective guards used to mitigate stock damage. Dynex sleeve on a 3-metre poplar pole (left), stainless steel cage on a rooted wand (right)

3.4.2 Installation of climate stations and the variables measured

Climate stations (Fig 12) were installed on north- and south-facing aspects at each farm (Table 10) to evaluate and compare the microclimate between aspects. The climate stations measured rainfall, temperature, wind direction and speed. The stations installed at Taumarunui, and Hawke's Bay were Davis Instruments GroWeather remote telemetered monitoring stations (Davis Instruments, Haywood, USA). An Onset HOBO RX3000 remote telemetered monitoring station (Onset Computer Corporation, USA) was installed at Wairarapa on the south-facing aspect. Once available, a monitoring station was installed on the north-facing aspect of the Wairarapa site. Monitoring occurred from the 16th of December 2021.

Fig 12: North-facing aspect climate station at the Hawke's Bay site

Table 10: Climate station installation dates and specifications at each trial site.

Location	Installation Date	Climate Station Specs
Taumarunui	28-Sep-21	Davis Instruments GroWeather
Hawke's Bay	22-Sep-21	Davis Instruments GroWeather
Wairarapa	16-Dec-21	Onset HOBO RX3000

3.4.3 Tree measurements (data collection)

Trials began in July 2021 in Wairarapa and Hawke's Bay and October 2021 in Taumarunui (Table 11). The later date at Taumarunui was as a result of the Covid-19 lockdown and travel restrictions. At planting, the locations of all trees were surveyed with a Trimble R10 GPS receiver operating in RTK mode (details in Section 3.6.1). The heights of each tree were measured with a tape measure and for 3-m poles the diameter at the top of each protective sleeve (approximately breast height) and at the base were measured with callipers. Subsequent visits assessed survival and growth.

3.4.3.1 Tree growth

Tree growth was assessed at two intervals after planting, the first at the start of summer 2021/2022 and the second at the end of summer 2022 (Table 11). Measurements included tree height for all poplar material (i.e., poles, wands, and rooted stock) using a tape measure or a telescopic measuring stick, and the diameter measurements were taken at the top of the protective sleeve (approximately breast height) and at the base using callipers for the 3-m poles. The diameter at breast height (DBH) is typically used to measure tree diameter at 1.37-m. Due to the presence of the Dynex sleeves preventing a DBH measurement, the diameter was instead measured at the top of the Dynex sleep of each pole (at a height of approximately 1.7 m), and at the base of the pole (i.e., just above the soil). For convenience in this thesis, the DBH terminology is used for the diameter measurement at the top of the sleeve. Due to the presence of tree guards preventing easy access to the trunks, and the absence of a consistent measurement reference, diameters of the wands and rooted stock were not measured. Growth was calculated as the difference in height, or diameter between measurement dates.

Table 11: Trial planting and measurement dates for all trial sites.

Sites	Dates		
	Planting	Start of summer measurement	End of summer measurement
Wairarapa	21/07/2021	4/01/2022	31/03/2022
Hawke's Bay	28/07/2021	18/12/2021	6/04/2022
Taumarunui	5/10/2021	21/12/2021	5/04/2022

3.4.3.2 Tree survival

Survival was assessed at the start and end of summer 2021/2022 at each site (i.e., at the same time the growth measurements took place) (Table 11). Survival was determined by the absence of leaves or shoots, or if the poplar material was broken (i.e., knocked over by cattle etc.) or missing. If trees did not survive between planting and the first measurement visit (i.e., no visible signs of shoot growth) the death was assumed to be attributed to planting shock. Planting shock (also referred to as transplant shock) is the reduced growth observed following transplanting of nursery stock (Struve, 1990). Further research is needed to better define and quantify the process of planting shock (Struve, 1990). If the trees did not survive between the first and second measurement, the death was assumed to be influenced by environmental factors if other causes such as stock damage could be ruled out (i.e., the poplar material was not broken/pushed over).

3.5 Processing and analysis of data (tree and climate)

To evaluate factors that might contribute to plant survival and favourable establishment, plant growth and survival data were statistically analysed with respect to factors that might influence them, such as topography and climate.

3.6 GIS

3.6.1 Data input

To quantify the topography at each site, a DEM for each farm of 15 m resolution (NZSosDEM V.1.0 (Columbus et al., 2011)) was downloaded from Koordinates as a GeoTIFF file and opened within ArcGIS Pro software (v. 2.7.0) for analysis. Each DEM was cropped to the farm boundary which was provided as a shapefile. GPS points of individual trees were added to provide reference points for spatial analysis. These GPS Coordinates were surveyed using a Trimble R10 GPS receiver (RTK mode), differentially correcting through a local base station against nearest LINZ continuous GPS station (providing < 10 cm accuracy).

3.6.2 Data manipulation

The DEMs for each farm were used to derive morphometric (i.e., topography) variables hypothesised to have a potential influence on tree survival. The variables included profile curvature, slope, topographic position index, topographic wetness index, wind exposition index (Table 12) and elevation and were measured in R (R Core Team, 2021) using the RSAGA packages (v. 1.3.0; Brenning et al., 2018) or qgisprocess (v.0.0.0.9; Dunnington, 2021).

Table 12: Description of topographic variables used in analysis

Topographic variables	Description
Profile curvature	Vertical plane curvature. When the cell value is < 0 the surface is convex, > 0 the surface is concave, and zero when the surface has no curvature/is uniform
Slope	Gradient in degrees
Topographic Position Index (TPI)	When the cell value is > 0 it is higher than its surroundings, < 0 it is lower than its surrounding, and zero when it is a flat area or mid-slope
Topographic Wetness Index (TWI)	Higher values correspond with higher surface wetness.
Wind Exposition Index (WEI)	Values < 1 indicate wind-shadowed areas, > 1 indicates areas exposed to wind

3.7 Tree growth and survival data

All field data (i.e., growth and survival data) were processed and converted to csv files to be imported to R. These data were pre-processed to address any gaps in GPS coordinates, or growth and survival measurements. Finally, trees were removed where deaths were assumed to have occurred from planting shock (i.e., deaths occurring between planting and the first measurement).

3.8 Statistical analysis

Code was written within R to calculate descriptive statistics (minimum, median, mean, maximum and standard deviation) for all potential explanatory variables (Section 3.6.2). Histograms were produced to show the correlation between morphometric variables and survival based on tree type and slope aspect separately. Establishment was examined through growth data analysis which undertook a similar approach by producing scatterplots to determine any correlation between morphometric variables on vertical growth rate of poles based on different trial sites and aspects separately. The growth data was analysed using the 3-m poles only, as they had more uniform initial growth and were planted to similar depths across all sites. Therefore, plant type was not analysed.

Additional to the descriptive statistics for the three trial sites separately, statistics (minimum, the first quartile (Q1), median (Q2), the third quartile (Q3), and maximum(Q4)) were also

calculated for the three sites and grouped on type and survival. A Spearman test was conducted to identify correlation between growth rates and explanatory variables between trial sites (hypothesis 1). Another Spearman test was conducted to identify correlation between growth rate and explanatory variables between aspects (hypothesis 2). Finally, a two-sided, two-sample t-test assuming unequal variance was performed to determine if any differences in growth rate between the two slope aspects at each farm and between farms were statistically significant (hypothesis 3).

The following hypotheses were tested:

1) Null: there is no significant correlation between the growth rates and the different explanatory variables for the different trial sites

   Alternative: there is a significant correlation between the growth rates and the different explanatory variables for the different trial sites

2) Null: there is no correlation between the growth rates and the different explanatory variables for north and south facing hillslopes

   Alternative: there is a correlation between the growth rates and the different explanatory variables for north and south facing hillslopes

3) Null: there is no difference between the growth rates of the poles on the north- and south-facing aspect slopes.

   Alternative: there is a difference between the growth rates of the poles on the north- and south-facing aspect slopes.

3.9 Climate data

The CliFlo climate station rainfall results for the trial period were compared with the rainfall results from the on-site climate stations. This aimed to show any difference between the datasets, thus identifying any faults or discrepancies and illustrating the effects of micro-climates. A second comparison was performed between the two climate stations at each site, to evaluate the effect of slope aspect on microclimate. The difference between solar radiation, rainfall, and temperature was statistically analysed using a 1-sided, 2 sample t-test.

The following hypotheses were tested separately for each of solar radiation, temperature, and rainfall:

- Null: there is no significant difference between north- and south-facing slope aspects
- Alternative: there is a significant difference between north- and south-facing slope aspects

The tests were run separately for the Hawke’s Bay and Taumarunui sites, to evaluate any differences between these locations. No Wairarapa data were included due to technical malfunction of the climate stations (Section 5.3).

3.10 Tree trial hypothesis

I hypothesised that there would be better survival and plant growth on the south-facing aspect than at the north-facing aspect of the Hawke's Bay and Wairarapa sites, but the opposite or little difference at the wetter Taumarunui farm. Further, I expected that there would be overall better survival and growth at Taumarunui than the drier eastern sites.

I hypothesised that the north-facing aspect to be warmer, drier and sunnier than the south-facing aspect. Further, I expected there to be higher survival coinciding with higher TWI values and lower TPI values (due to expected greater accumulation of surface and sub-surface runoff in these locations). For similar reasons, I expected higher survival coinciding with higher Profile Curvature values which would indicate concave slopes. I expected lower survival at higher elevations which would correlate with higher WEI values and slope gradients.

Chapter 4 Results

4.1 Study 1: Semi-structured interviews

4.1.1 Perceptions of the use and effectiveness of poplars to mitigate hill country erosion

In response to question 5, the survey found that 40% of the participants stated their preference of willows for addressing erosion in the Gisborne and Manawatū-Whanganui regions due to the main types of erosion these regions service and their perceived superior root networks and better survival in wet environments, stating:

> "In terms of riverbank and gully planting, the preference is willows." Participant 1

Some reasons for why willows are more successful in gullies and riverbank erosion were:

> "...due to their root structure. Willows have a lot more smaller roots concentrated closer to the trunk. Willow root systems develop close to the surface and extract and transpire water at a much higher rate." Participant 5

Therefore, the consensus for all surveyed participants was that willows generally are more successful in wetter environments. However, two participants noted the poor public perception of willows in their respective regions due to extensive invasion of crack willow in waterways in the Wairarapa and the ongoing management of willows planted on farms in Gisborne, stating:

> "...the weight of the limbs are starting to split apart because they don't have a single leader like poplars do. They're splitting apart and disease is getting in so the older ones are starting to die off and cause problems with farmers not being particularly impressed with the amount of debris." Participant 1

It was unanimously agreed that poplars remain a popular choice in pastoral systems addressing hillslope erosion mostly due to their ease of establishment, particularly in the presence of stock.

Effective planting requires adequate understanding of planting practices which was evidenced by 40% of the survey participants, noting the observation of incorrect tree placement on current movements or old scars (i.e., planting in locations where it is too late, and the land has already failed). In some regions where farmers plant their own poplar poles, there are several issues arising including not correctly identifying where to plant and not knowing how many trees are required in a given area:

> "...there is a perception that you have to plant a lot because you can expect some to die …they're over planting and getting them quite close (5-7m spacing) which is wasting poles unfortunately. Now that poles are getting harder to come by and more expensive to produce, it's time to take stock and re-educate people about how to make the best use of them". Participant 3

All participants stated that space planted poplars are an effective tool for treatment of highly erodible land, an example of why they are so effective is their root systems and can be evidenced in the research:

> "...the reason why space planted poplars work so well is that their root systems extend so far out from the trunk of the tree, more so than possibly any other tree I know." "[there are] two quite extensive studies in the Wairarapa, southern- and northern-Hawke's Bay and the Manawatū-Whanganui regions around the effectiveness of space planting poplars and willows following serious storms. There is no doubt that they reduce erosion from 30% of the slope down to less than 5% of the slope". Participant 5

4.1.2 Measuring planting success and effectiveness

From the survey, 60% of the participants indicated that tree survival is an important measure of planting success, 40% indicating the importance of growth data as well. The following statements were made:

> "...you don't just plant for erosion control, you also plant for greenhouse gases emissions, for amenity, and for stock shelter. So, to measure the success of a planting there should be a straight up pole count." Participant 1

> "The first measure of effectiveness is survival. During the first two years, if the pole survives, potentially it's effective. Then it's about how fast it grows." Participant 5

> "...it takes about five years for a planted pole to be effective as being able to hold erosion. If they can get through to that age, then it's taken that the land is treated." Participant 4

Survival audits have been conducted in the Greater Wellington Region for a number of years with the purpose of identifying patterns for maximising survival. This has been recognised as a strength from other regional councils, with one participant remarking:

> "GW are doing that already; they have a well-developed system of record keeping and a very comprehensive descriptive system of what's happening on site etc. we will probably borrow a bit of methodology from them." Participant 3

Eighty % of the participants noted that nothing formal is collected or any measurements of sediment delivery into waterways taken. It was mentioned by two of the participants that not all sediment will make its way to the waterways and therefore this method alone won't tell the full story of any catchment. However, there was mention of the use of sediment monitoring devices in one region, but more information is needed, evidenced by:

> "Apparently there are methods where you can attach signatures to your sediment and determine what's being remobilised in the channel, opposed to what's being introduced to the channel by erosion events. But we are not at the stage where we have that level of monitoring or research in place." Participant 3

Another means to measure planting success mentioned by 60% of the participants is by evaluating imagery or the use of past research. Imagery allows for a quick survey and cautions were given:

> "...studies that look at post storm losses which look for slips from aerial photos don't see gully erosion or sheet erosion." Participant 2

> "...you have to ground truth that sort of stuff. You do see a lot of things when you walk the ground, you see things you won't pick up with imagery." Participant 5

> "We rely a lot on the Landcare research after Cyclone Bola, where they compared erosion to adjacent sites with pasture versus mature canopy cover. There is still a certain amount of historical research that still guides us today." Participant 3

4.1.3 Responses to planting techniques

The most common planting technique across 100% of the participants is to drive a pole in (i.e., using a pole bar, also referred to as a pole driver) after forming a guide-hole using a crowbar, auger or similar implement. The two-handle pole drivers have been used in Hawkes Bay for decades, but it was suggested that the Y-bar pole driver that was developed by Greater Wellington provides more control to the planter. However, one participant noted

> "The best planting technique is dependent on the site." Participant 2

One of the overarching messages that came from all regional councils was the importance of achieving an adequate planting depth (minimum 700 mm) to increase interception of moisture and packing soil tightly. Use of an auger to form the guide-hole was mentioned in multiple conversations and was most commonly recommended for creating a deeper guide-hole in difficult terrain. The diameter of the auger was an important point, and if a thicker auger was used, it was recommended to return in the summer (when soils are drying out and shrinking) to re-ram the poles and make sure the soil is tightly packed. The perceived

disadvantages of using augers were the practical and safety factors, considering another piece of equipment is being moved around the hillslopes. It was also mentioned that in clay rich soils, the auger can cause a glazing effect within the guide-hole creating increased difficulty for root penetration. In some regions, other methods such as digging with spades have been used to achieve adequate depth.

> "We are getting more people digging poles in, saying they're getting better survival. The main advantage is getting poles deeper into the ground. Driving them can be hard to get into the minimum 700 mm." Participant 3

Planting technique is not considered a major cause of death in the Greater Wellington region due to planting supervision and use of experienced contract planters. However, experienced contractors are used because quality planting is important:

> "If a pole has died, and everything else being equal, all the ones around it have survived, it would have died from poor planting." Participant 4

4.1.4 Perceptions of survival factors

When asked what the most influential factors were to survival in each region, 100% indicated climate, 80% indicated adequate siting, 60% indicated stock protection and 40% indicated poplar variety.

In more challenging terrain, participants suggested realistic decision-making and doing the basics right. There was specific mention of planting to depth to achieve water access and therefore ensuring the site has adequate soil depth.

> "...you have to be a bit realistic and make a call whether it's pole country or not. Make some tougher calls and look for alternatives." Participant 3

> "You have got to make sure that everything else is on point because you have less margin for error. If you are in those harder sites, you have got to have the right variety, and they have got to be good quality poles. You make sure they are planted to depth, so they have the biggest access to water they can. You give them the best chance." Participant 4

The final question was a multi-choice rating system for a number of survival factors considered to be influential. The perceived importance of potential survival factors appears regionally specific as expected. There was general agreement on factors considered as important and very important including planting timing, species and varieties, climate, topographic position, stock presence, and planting quality. However, there was a significant

spread of responses regarding where on the stem the poles are cut. There was also a reasonable spread of responses for factors as indicated in Table 13.

Table 13: Responses from 5 interview participants for Question 8 of the survey indicating the number of responses to each influential factor option

Factors that may affect survival of poles:	No influence	Very little influence	Some influence	Important factor	Very important factor
Time of year poles are harvested		●		●●	●●
Time of year poles are planted (Mid May - Sept)				●	●●●●
Duration of time between harvest and planting			●	●●●	●
Method of water poles after harvest		●●	●●	●	
Supply of water for poles (e.g., chlorinated, stagnant, pond, creek, anaerobic muddy bottom)		●●		●	●●
Where on the stem the poles were cut	●		●	●●	●
How the ends are prepared for planting		●●	●●		●
Size of the pole (diameter)				●●●●	●
Transport of poles (wind drying, rough handling etc.)		●●	●●	●	
Consideration of species and limitation of varieties when planting				●	●●●●
Choice of planting techniques		●	●●●	●	
Climate and rainfall				●	●●●●
Topography (e.g., slope gradient, landform)				●●●●	●
Lithology			●	●●	●●
Soil type			●●	●	●●
Wind exposure			●	●●●	●
Position in the landscape with regard to micro-topography (e.g., small depression)				●	●●●●
Presence of stock and pests				●	●●●●
Pests and diseases		●●●●		●●	
Weed spray (e.g., thistle spray)			●●	●	●●
Quality of planting (i.e., depth, re-rammed)				●	●●●●
Length of time between soaking and planting				●●●	●●

4.2 Study 2: Tree establishment trial

4.2.1 Tree survival

Survival was high across all trial sites. Of all the poplar material planted, 90.4% survived, 4.3% died and 5.3% were lost from planting shock (Appendix B). The highest survival occurred at the Hawke's Bay site; the highest number of planting shock losses occurred at the Wairarapa site, and the highest number of deaths occurred at the Taumarunui site (Fig 13). North-facing aspects had slightly higher planting shock losses and south-facing aspects had slightly higher survival (Fig 13).

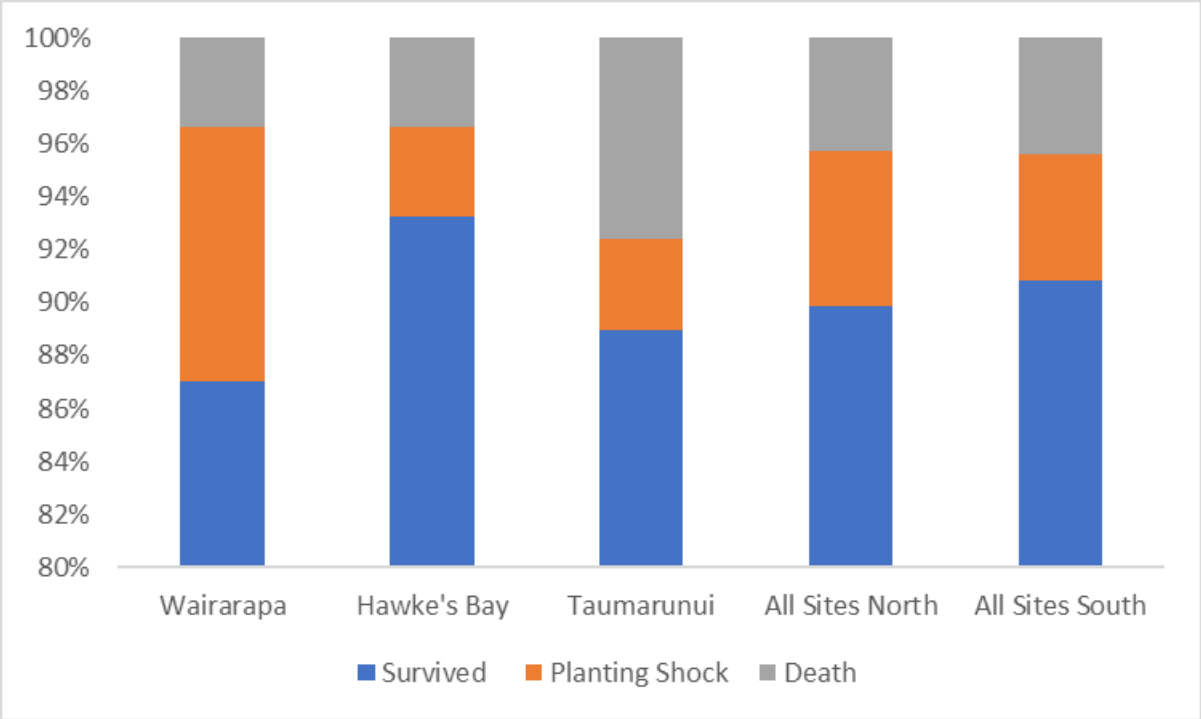

Fig 13: Percentage of survival, planting shock losses and death across the three trial sites and all north- and south-facing trees combined

Wairarapa had the highest average pole survival and lowest root wand survival (Fig 14). Hawke's Bay has the highest average survival for unrooted wands and the lowest for poles. All south-facing aspects combined had the highest average pole survival and lowest average rooted wand survival (Fig 14).

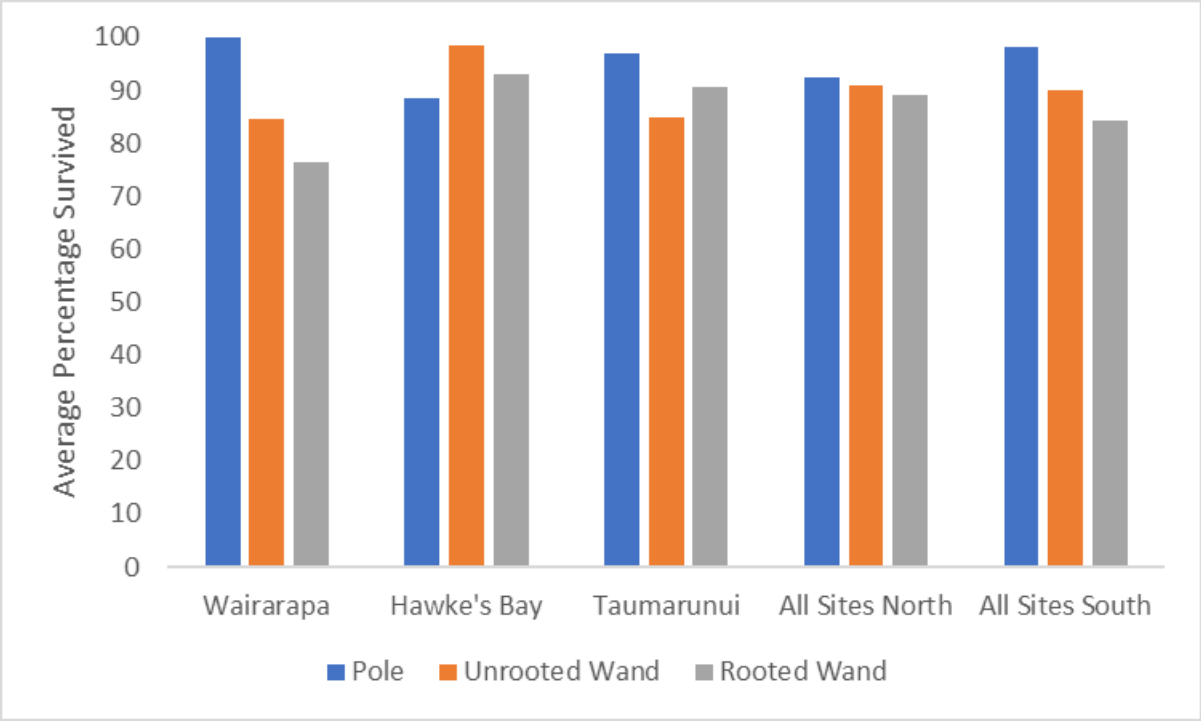

Fig 14: Average percent survival for poles, unrooted and rooted wands across the tree trial sites and all north-facing and south-facing trees

4.2.1.1 Wairarapa

The total deaths for the Wairarapa trial site were 14 rooted and 9 unrooted wands; no poles died at this site (Appendix B). Wairarapa had the most losses from planting shock of all the trial sites, with planting shock attributing to 74% of the total losses (i.e., losses from deaths and planting shock) at that site, and 33% of the total losses from all the trial sites combined. The rooted wands on the south-facing aspect had the biggest combined losses. Losses from this aspect appear to be clustered throughout the middle section of the planted area but spread across different slope heights (Fig 15).

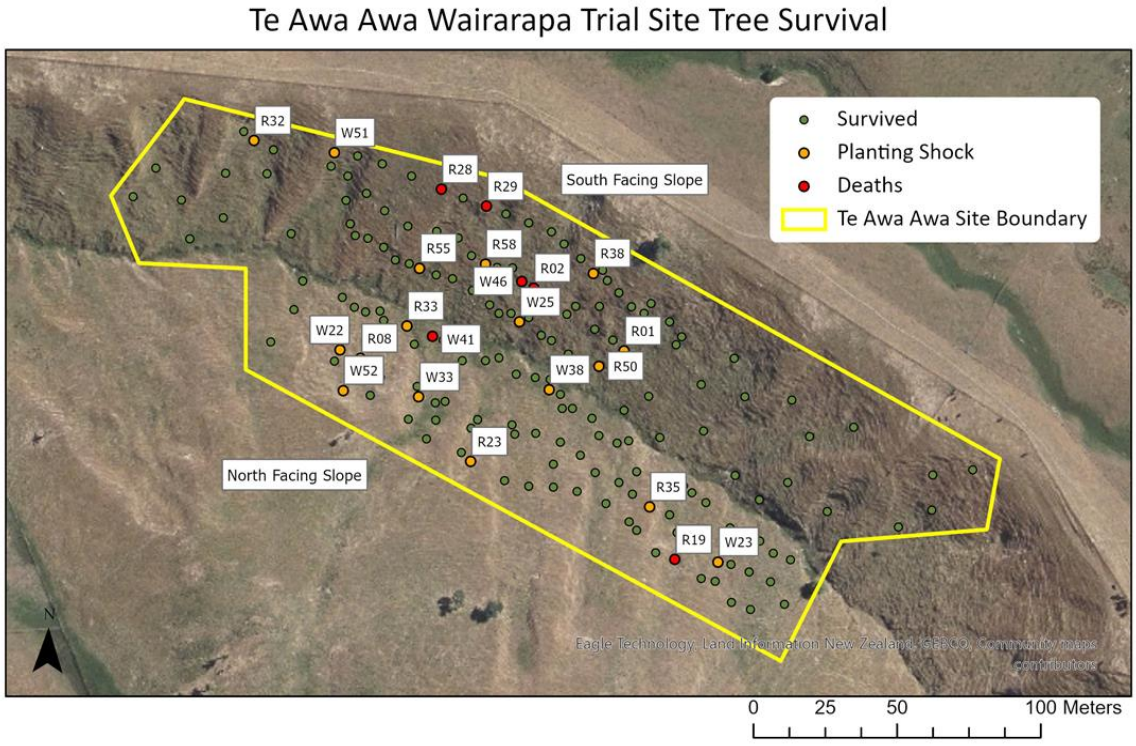

Fig 15: Map of Wairarapa trial site showing the planting site boundary (yellow), survived trees (green), trees lost from planting shock (orange), and deaths (red). Labels are included for trees that experienced planting shock losses or death. R represents rooted wands; W represents unrooted wands.

4.2.1.2 Hawke's Bay

The Hawke's Bay trial site had equal losses from planting shock and deaths (Appendix B). Planting shock losses were split evenly across the north- and south-facing aspects. The greatest combined losses were from poles on the north-facing aspect and rooted wands on the south-facing aspect. Losses at the north-facing aspect were greater at the top of the slope (Fig 16), whereas losses at the south-facing slope were spread across different slope heights (Fig 16).

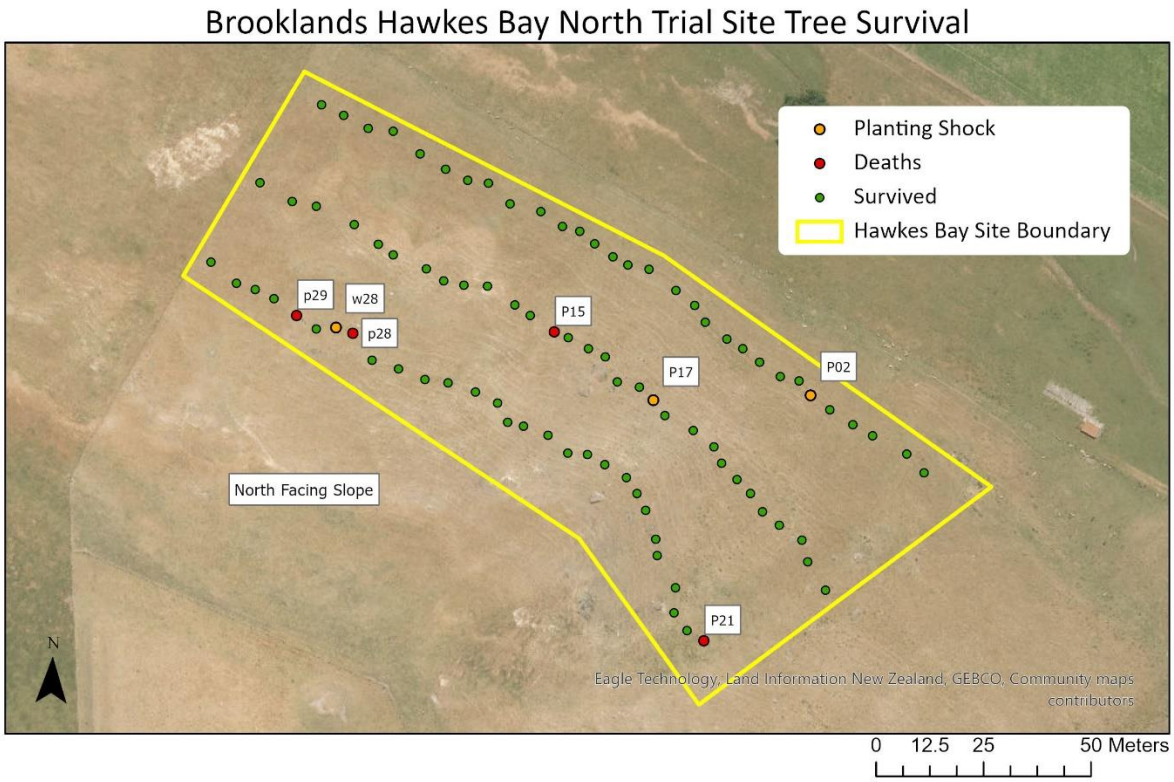

Fig 16: Map of Hawkes Bay north and south trial sites showing the planting site boundary (yellow), survived trees (green), trees lost from planting shock (orange), and deaths (red). Labels are included for trees that experienced planting shock losses or death. P represents poles, W represents unrooted wands, SR represents rooted wands on the south-facing site, and SP represents poles on the south-facing site.

4.2.1.3 Taumarunui

The Taumarunui trial site has the highest deaths across all the trial sites, attributing to 68% of the total losses from the Taumarunui trial sites and 48% of the total combined deaths from all trial sites (Appendix B). The distribution of losses is evenly spread throughout slope heights at the north-facing slope and concentrated at the northern and southern ends of the trial site (Fig 17). The most deaths occurred in the unrooted wands on the south-facing aspect and there was reasonable spread across slope heights and throughout the site boundary (Fig 18). There were 19 wands that received alternative protective guards, 63% survived, 6% died as a result of environmental factors and 5% died from planting shock (Appendix B).

Fig 17: Map of Taumarunui north-facing trial site showing the planting site boundary (yellow), survived trees (green), trees lost from planting shock (orange), and deaths (red). Labels are included for trees that experienced planting shock losses or death. NR represents rooted wands, NW represents unrooted wands, and NP represents poles.

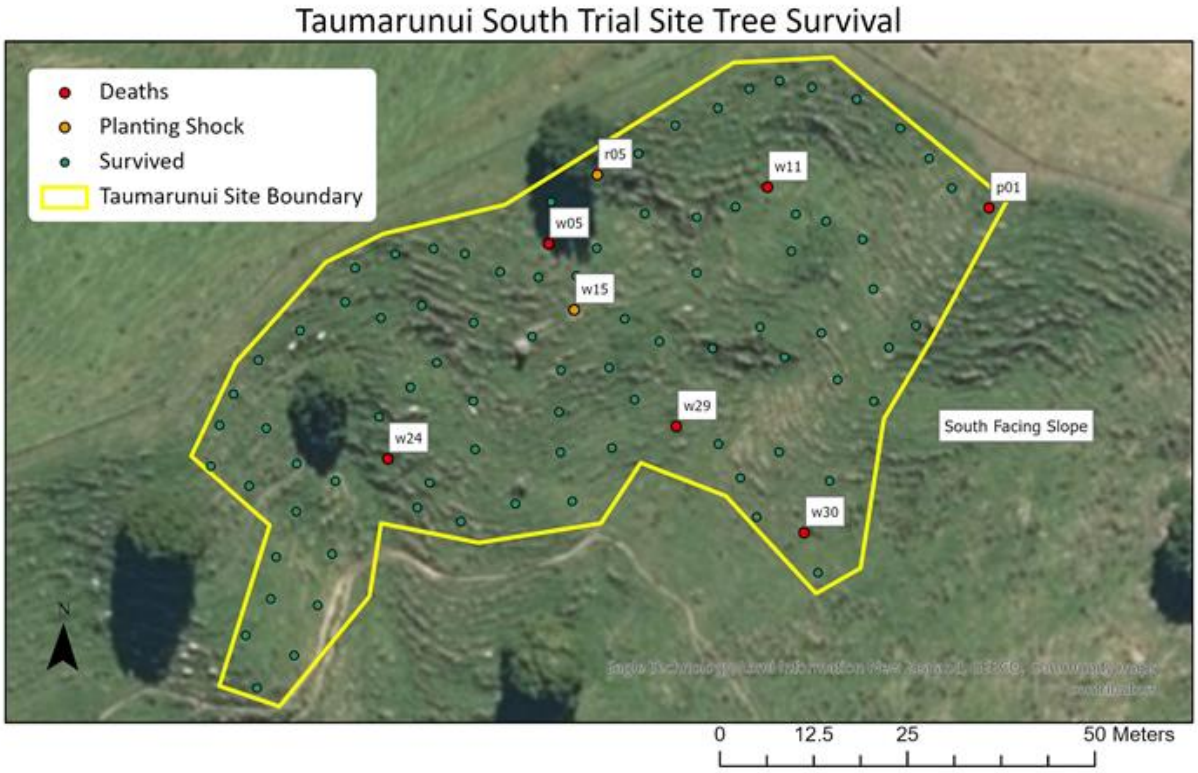

Fig 18: Map of Taumarunui north-facing trial site showing the planting site boundary (yellow), survived trees (green), trees lost from planting shock (orange), and deaths (red). Labels are included for trees that experienced planting shock losses or death. R represents rooted wands, W represents unrooted wands, P represents poles.

4.2.2 Climatic variables

4.2.2.1 CliFlo climate monitoring station data

4.2.2.1.1 Long-term rainfall data

Compared to the long-term average rainfall, there was more rainfall than expected during the trial period (Section 3.4.3; Table 11) for the two eastern sites (Wairarapa and Hawke's Bay) and less rainfall than expected at the western site (Taumarunui). The Wairarapa and Hawke's Bay data shows there were no severe droughts during the 2021-2022 trial (Fig 19 A and B respectively) and the cumulative deviation suggests that the trial period (2021-2022) was wetter than the long-term average. In Taumarunui, the trial period appears to be drier than in previous years (Fig 19 C). This rainfall data suggests the trial period occurred over an 'abnormal' season relative to long-term rainfall averages. Therefore, rainfall could explain why there were high rates of survival, particularly at the drier eastern sites.

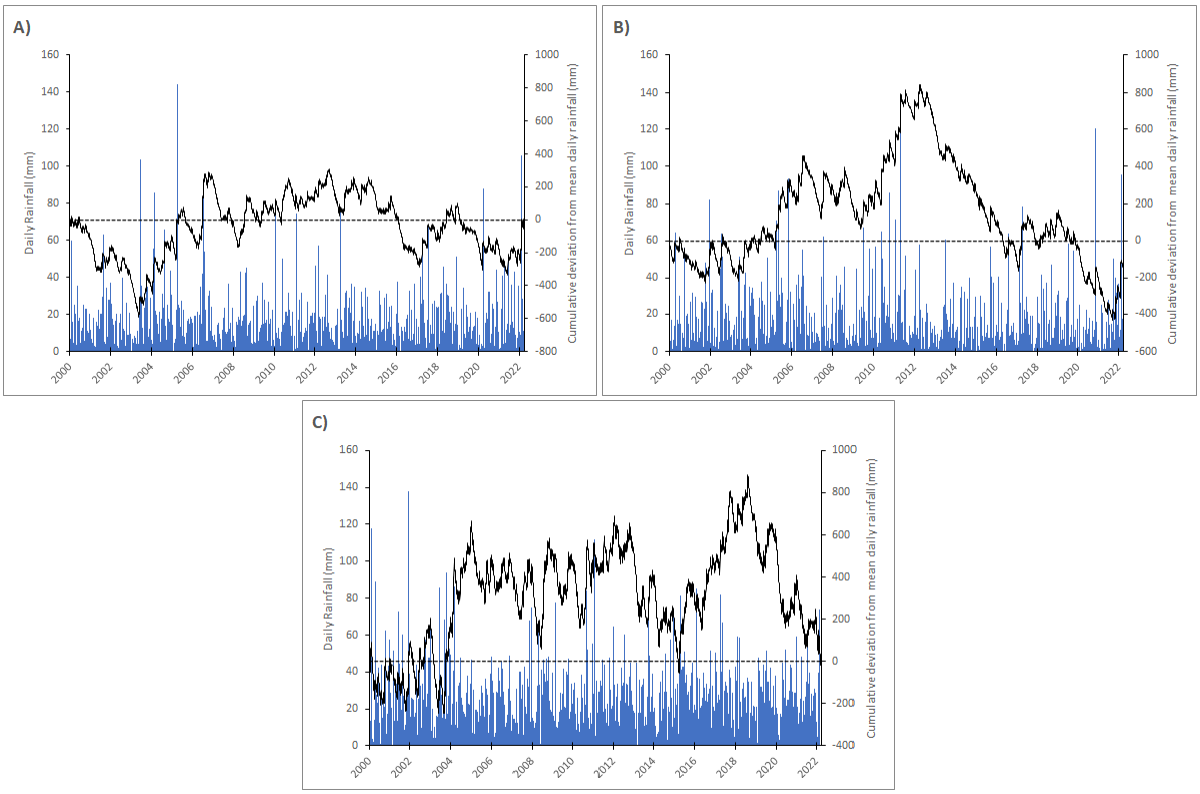

Fig 19: Long-term rainfall data for Gladstone, A) Wairarapa (Climate Station Agent no. 2613); B) Hawke's Bay (Climate Station Agent no. 2980); C) Taumarunui (Climate Station Agent no. 2264) showing daily rainfall (blue bars) and cumulative deviation from mean daily rainfall (black line) for the period 01/01/2000 to 31/03/2022. (Data downloaded from the CliFlo database).

4.2.2.1.2 Three-year rainfall data

The unseasonal rainfall patterns are further exemplified by graphs showing a more detailed view of rainfall for the 3-year period prior to and inclusive of the trial period for each trial site (Fig 20). Both the Wairarapa (Fig 20A) and Hawke's Bay (Fig 20B) summer period (highlighted in grey) during the trial period (highlighted in yellow) experienced an increase in cumulative deviation from mean daily rainfall (black curve of Fig 20), rather than the decrease seen for the two previous summer periods (and usually expected of summer in this region). Taumarunui (Fig 20C) on the other hand shows a decrease in cumulative deviation from mean daily rainfall for all three summers, though the drop is less pronounced for the trial period due to a large late-summer rainfall event (seen at each of the sites).

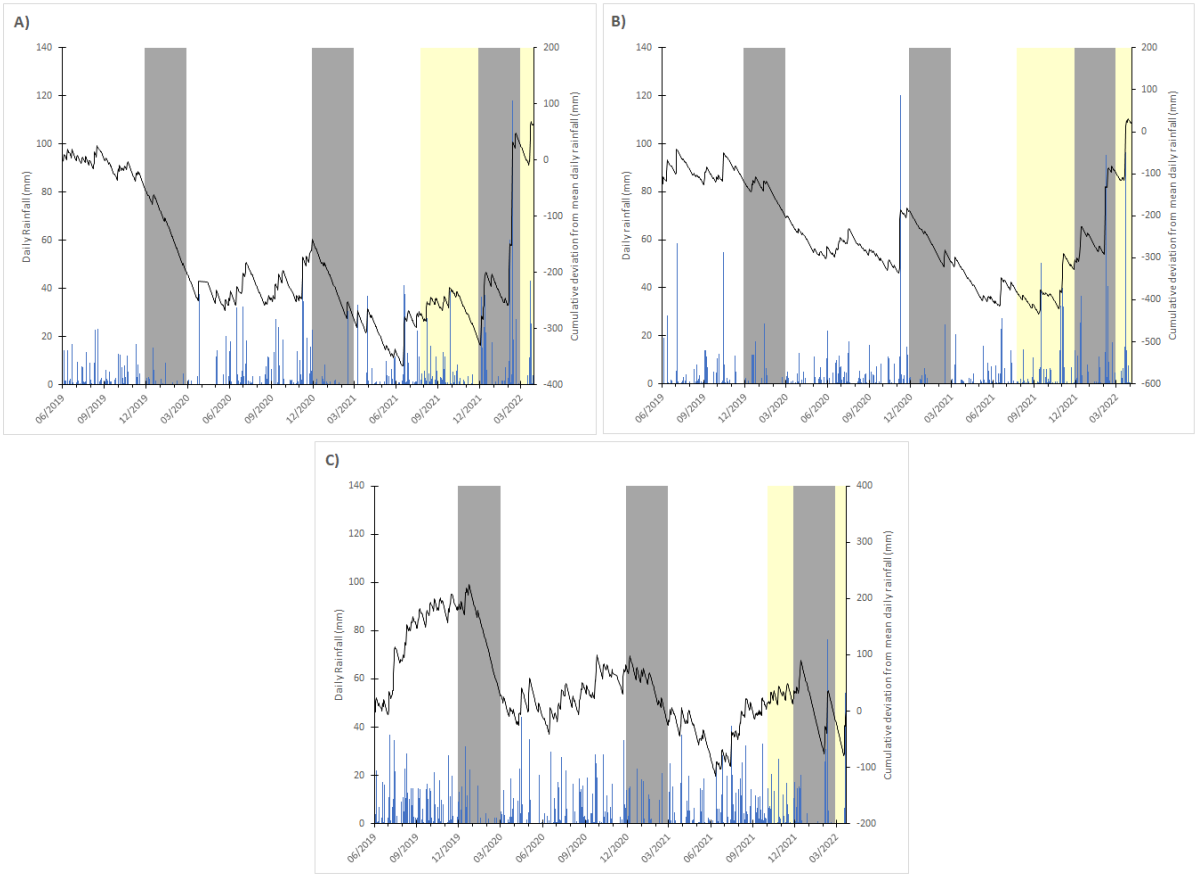

Fig 20: Rainfall Data for A) Wairarapa (Climate Station Agent no. 40984); B) Hawkes Bay (Climate Station Agent no. 2980); C) Taumarunui (Climate Station Agent no. 35135); showing daily rainfall (blue bars) and cumulative deviation from mean daily rainfall (black line) for the period 04/06/2019 to 31/03/2022. The experimental trial period is shown in the yellow shaded areas and summer months (December to February) are shown in the grey shaded areas (Data downloaded from the CliFlo database).

4.2.2.2 NIWA and on-site climate monitoring station data comparisons

The difference in the total accumulated rainfall between the nearest NIWA climate monitoring station and the on-site climate monitoring stations were 452.8mm, -29.6mm, and 121.4mm for Wairarapa, Hawke's Bay and Taumarunui respectively. These results evidence variable climate conditions across relatively short distances (Section 3.3.2; Table 4) and highlight a malfunction in rainfall measurement at the Wairarapa site. The NIWA CliFlo data, which are considered more reliable, were therefore used for the following comparison at the Wairarapa site. The difference between the total rainfall collected during the trial periods (Section 3.4.3; Table 11) and the long term 22-year average over the same period of the year (Table 14) was 279.7mm, 280.3mm, and -219.5mm for the Wairarapa, Hawke's Bay and Taumarunui sites respectively. This shows a similar increase in rainfall for the two eastern sites and a reasonably similar decrease in rainfall for the western site. From the above analyses, it is concluded that the trial period did not occur in a 'typical' season.

Table 14: Rainfall data for the trial period (Wairarapa: 21/07/21 - 31/03/2022; Hawke's Bay: 27/07/2021 - 06/04/2022; Taumarunui: 05/10/2021 - 04/04/2022) based on the nearest CliFlo climate monitoring station and the average of the north- and south-facing on-site climate monitoring stations. The average trial period and annual average were calculated across 22-years from the nearest CliFlo climate monitoring station data. (Agent nos. 2613; 2980; 2264)

Trial sites	Rainfall (mm)			
	Trial period (CliFlo station)	Trial period (Trial climate station)	Trial period average (CliFlo station)	Annual average (CliFlo station)
Wairarapa	846.2	393.4	566.5	871.4
Hawkes Bay	752.6	782.2	501.9	790.4
Taumarunui	666.4	545	764.5	1757.1

4.2.2.3 On-site climate monitoring station data comparisons

In the Hawke's Bay, the solar radiation on the north-facing slope was significantly greater than the south (*p-value* = < *0.001*) (Fig 21). The temperature was not significantly different (*p-value = 0.304*). Similarly, rainfall was not significantly different (*p-value = 0.496*). However, some differences between aspects can be seen during rainfall events in late March.

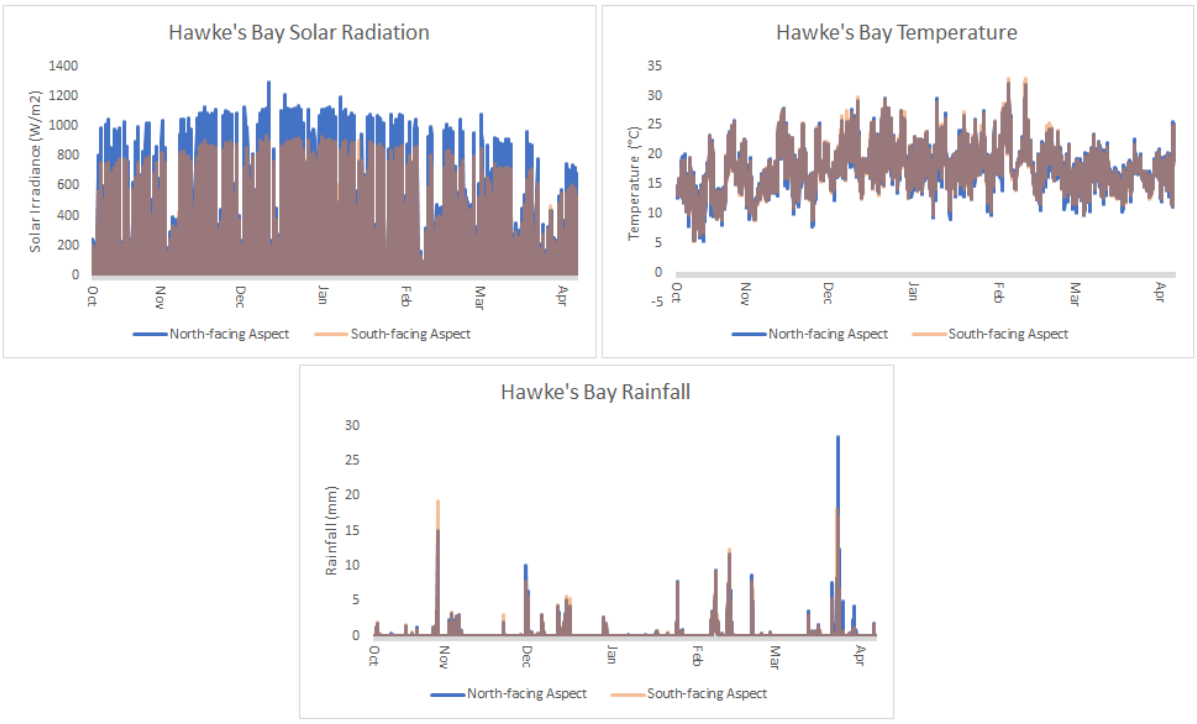

Fig 21: Climate monitoring station data comparisons for Hawke's Bay (solar radiation, temperature, and rainfall)

In contrast, the north- and south-facing aspects in Taumarunui did not have a significant difference (*p-value* 0.459) with slightly higher solar radiation on the south-facing aspect (Fig 22). Differences between aspects in terms of rainfall was also not significant (*p-value* =

0.405), however some difference was seen between aspects during single rainfall events (Fig 22). The temperature was significantly lower on the south-facing aspect (*p-value* 0.008).

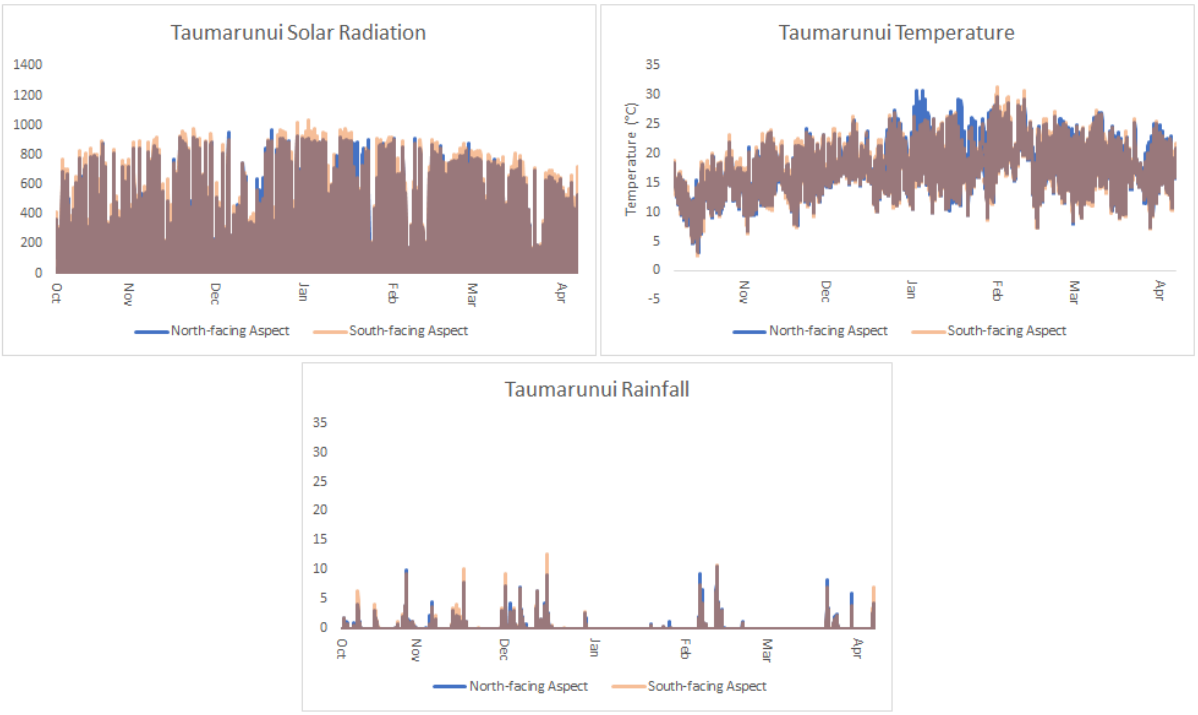

Fig 22: Climate monitoring station data comparisons for Taumarunui (solar radiation, temperature, and rainfall)

4.3 Morphometric variables

The morphometric variable means (Table 15) show that on average, poplar materials were planted on marginally convex slopes across all survival statuses except for Taumarunui where on average, survived and non-survived poplar materials were planted on marginally concave slopes. There appears to be no relationship between mean profile curvature and survival. Mean slope gradient is different between sites, the Wairarapa site shows lower mean slope gradients with planting shock occurring on the lowest mean slope gradient (10.3°) and deaths occurring at a mean slope gradient of 11.2°. At the Hawke's Bay and Taumarunui sites, there appears to be a trend showing deaths at the steepest mean slope gradient (25.9° and 25.1° respectively) and very similar slope gradients for survival and planting shock. For all sites, the lowest mean TPI was associated with deaths, the same is true for mean TWI, except for the Taumarunui site. The WEI is the same across all sites and all survival statuses. Deaths occurred at the lowest mean elevations at Hawkes Bay and Taumarunui at 83.3 masl and 329.9 masl respectively. The elevation of all survival statuses at the Wairarapa site were very similar.

Table 15: Morphometric variable means for profile curvature, slope gradient, topographic position index (TPI), topographic wetness index (TWI), wind exposition index (WEI) and elevation across three trial sites, based on survival status

		Morphometric variable means					
Location	**Survival**	**Profile curvature**	**Slope gradient (°)**	**TPI**	**TWI**	**WEI**	**Elevation (masl)**
Wairarapa	Yes	-0.0021	12.7	-7	10.6	0.9	302.4
	No	-0.0031	11.2	-5.9	10.3	0.9	301.1
	Planting shock	-0.0025	10.3	-6.6	11	0.9	299.9
Hawke's Bay	Yes	-0.0023	19.8	-4.1	8.9	0.9	86.8
	No	-0.0004	25.9	-1.1	8	0.9	83.3
	Planting shock	-0.0022	19.7	-3.8	8.9	0.9	87.9
Taumarunui	Yes	0.0019	23.4	4.9	7.6	1.2	332.5
	No	0.0022	25.1	2.8	7.7	1.2	329.9
	Planting shock	-0.001	23.5	3.4	7.8	1.2	330.3

*curvature: 0 = no curvature/uniform; <0 = convex; >0 = concave

4.3.1 Morphometric analysis

The histograms produced show survival compared with the morphometric variables (Fig 23). The histograms show there is a slight trend towards non-survival and concave profile curvatures and survival and convex profile curvatures. Slope gradient had the greatest deaths at the mid 20° slopes and when the TPI indicated a flat area or mid-slope position. There were plant deaths at lower TWI values, signalling less water availability. There was a spread of deaths between wind-shadowed areas and wind-exposed areas but there was more in the latter. Overall, it was determined that the sample size of the losses was so small that it is unreliable to make representative inferences from the results of the survival data.

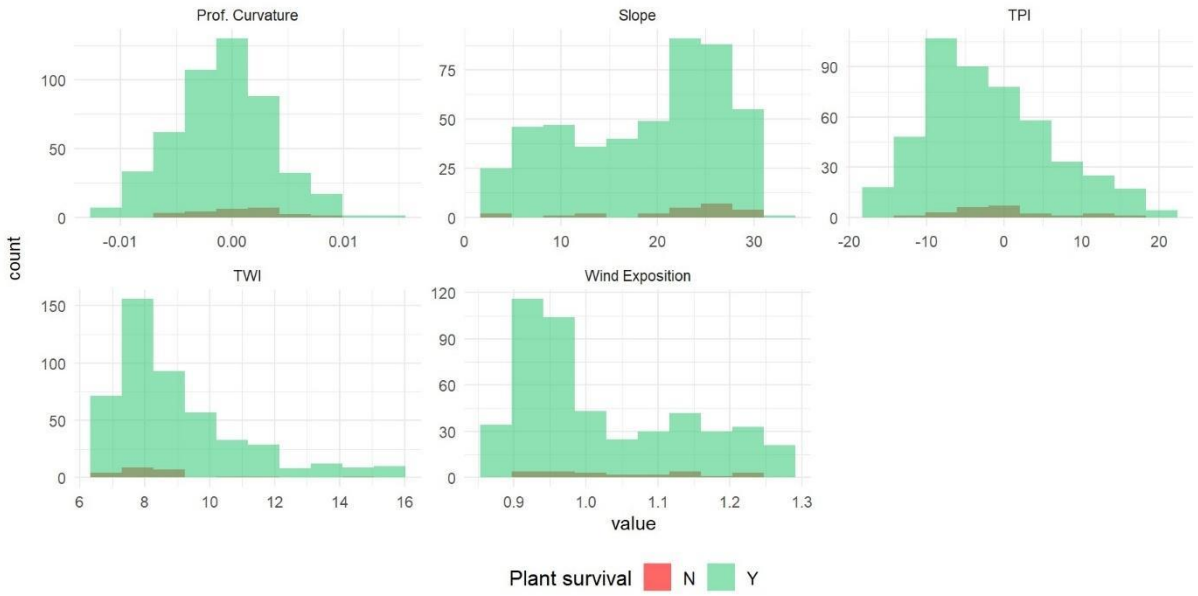

Fig 23: Morphometric variable analysis results based on plant survival.

4.3.2 Tree growth

Tree establishment was monitored, and tree growth was analysed as a proxy for survival or establishment success due to low numbers of non-survival.

4.3.2.1 Growth between different sites

The *p-values* are above the significance level (0.05) for all sites relating to profile curvature, slope, and TWI, suggesting there is no significant correlation between growth rates and the different explanatory variables for each of the sites (Fig 24). However, TPI at the Wairarapa site and WEI at the Hawke's Bay and Wairarapa sites are below the significance level (0.05) and thus we can reject the null (Section 3.8; Hypotheses 1) for these explanatory variables for these two sites. There are positive correlations between TPI and WEI and growth at the Wairarapa site, indicated by the R values of 0.32 and 0.27 respectively. This is inconsistent with the other sites which show negative correlations (although insignificant). There is a negative correlation between WEI and growth at the Hawke's Bay site indicated by an R value of -0.3.

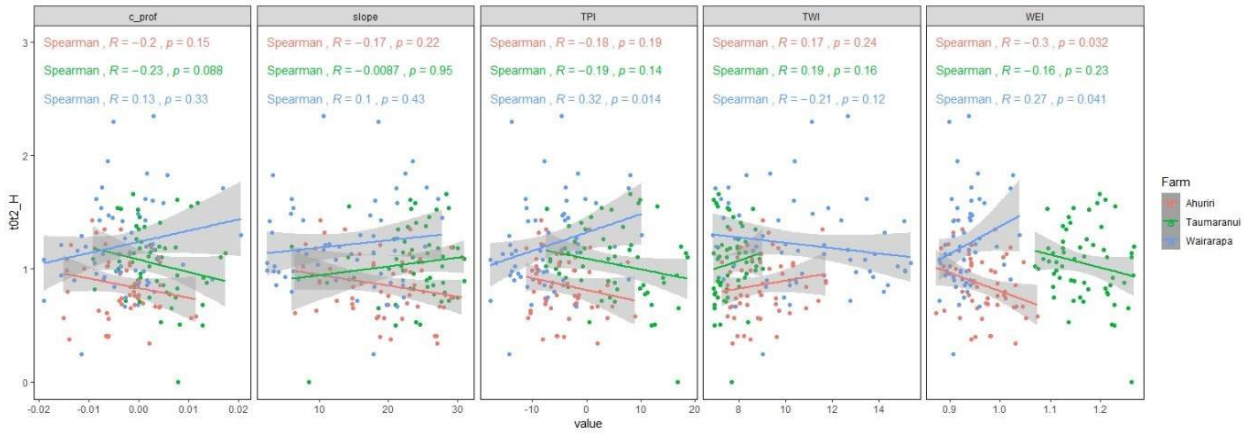

Fig 24: Relationships between growth (y-axis) and the morphometric variables: profile curvature (c_prof), slope, TPI, TWI and WEI. Relationships are shown separately for each trial farm, distinguished by colour (see legend), and the Spearman correlation R score and p-value is shown for each relationship.

4.3.2.2 Growth between different aspects

4.3.2.2.1 Morphometric explanatory variables

The *p-values* are above the significance level (0.05) for all explanatory variables at both north- and south-facing slopes (Fig 25) suggesting there is no significant correlation between the growth rates for the different explanatory variables when evaluated separately for the north and south facing hillslopes (combined for all farms) (Section 3.8; Hypotheses 2).

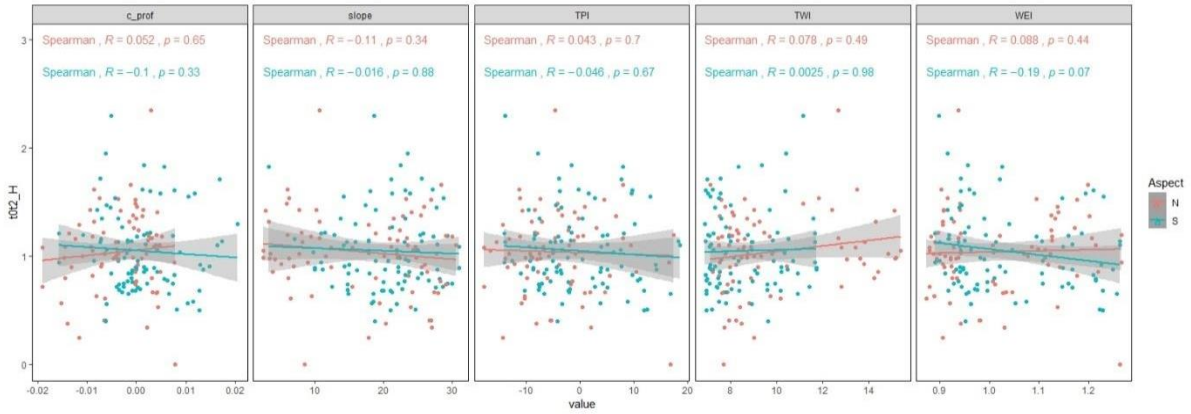

Fig 25: Relationships between growth (y-axis) and the morphometric variables: profile curvature (c_prof), slope, TPI, TWI and WEI. Relationships are shown separately for north and south aspects, distinguished by colour (see legend), and the Spearman correlation R score and p-value is shown for each relationship.

The mean growth rates are higher on the south-facing aspect for plant types at the Wairarapa site; for poles and rooted wands at Taumarunui; and for poles at the Hawkes Bay site (Table 16).

Table 16: Mean growth rates and standard deviations (SD), distinguishing between all tree types and north- and south-facing aspects at each trial farm.

Farm	Type	Aspect	Mean height growth (m)	SD (m)
Wairarapa	Pole	N	0.29	0.20
	Pole	S	0.74	0.64
	Rooted	N	0.04	0.07
	Rooted	S	0.08	0.09
	Wand	N	-0.11	0.51
	Wand	S	0.14	0.11
Hawke's Bay	Pole	N	0.36	0.11
	Pole	S	0.50	0.16
	Rooted	N	0.10	0.12
	Rooted	S	0	0
	Wand	N	0.31	0.14
	Wand	S	0.25	0.24
Taumarunui	Pole	N	0.43	0.19
	Pole	S	0.51	0.19
	Rooted	N	0.05	0.18
	Rooted	S	0.13	0.19
	Wand	N	0.04	0.25
	Wand	S	0.03	0.27

The t-test to evaluate differences in pole growth rate between north and south aspects indicated a significant difference in mean growth (*p-values* < 0.05) (Appendix B), with mean growth for the north-facing aspect of 0.36 m and mean growth for the south-facing aspect of 0.59 m.

Chapter 5 General discussion and conclusion

5.1 Current knowledge and information

5.1.1 Interviews with industry experts and practitioners

The information provided from the participants of the regional council interviews were largely regionally specific, as expected. There was general agreement between the responses from Hawke's Bay Regional Council and Greater Wellington Regional Council, which is unsurprising due to the similar East Coast climate regime.

5.1.1.1 Perceptions of poplar use

All industry experts and practitioners recognised the use of poplars as an important tool for erosion control purposes on open hillslopes. However, in regions where gully and riverbank erosion are high priorities, such as Gisborne and the Manawatū-Whanganui, willows are recommended. All regions captured in the interview process still commonly use poplars in pastoral systems to address shallow landslide erosion. This regional preference appears to be dependent on industry practitioner opinion and advice, and landowner perception and experiences. For example, there is poor public perception for willows in the Gisborne region due to high amounts of debris from older willows. There have also been negative experiences with high numbers of historic crack willows (*Salix* × *fragilis*) in river networks in the Wairarapa region that have led to multi-generation aversions to willows by landowners.

The inclusion of poplars prevails in all regions due to their single leader form which is preferred in pastoral systems, and their ease of establishment (particularly in the presence of stock). In Hawke's Bay where landowners are responsible for planting of poplars, there was a recognised need for ensuring that good placement of poles is achieved. The survey indicated that inexperienced planters tend to plant on a landslide scar (where the damage has already been done) or in very close densities which is causing ongoing issues such as low survival and poor growth and form. Poplars can be used to address deeper-seated erosion due to their ability to grow deeper roots, faster. For example, poplars make good pilot species to regain slope stability before planting seedling species that take longer to establish. It was acknowledged that space planting trees offers a solution to mitigating erosion where forestry planting is not practical or economical. Forestry planting requires a system change and some areas do not respond well to this planting system due to the

added weight of high numbers of trees planted on hillslopes. Contrastingly, there are some areas and erosion types for which forestry or native reversion is more appropriate. The research studies referred to by Participant 5 show the quantified capacity for space planted trees to be an effective tool for erosion mitigation and continued pastoral farming.

5.1.1.2 Planting effectiveness/success

There was an overall opinion that measuring planting success through measuring sediment loss is not plausible due to the current lack of readily available technology. There was concern noted about the reliability of results given by different in-stream monitoring devices, and a need to refine sediment fingerprinting or similar technologies to confidently identify sediment origins that are not currently accurate enough to measure planting success. Furthermore, it was agreed that only a proportion of total sediment from erosion processes will enter waterways and there is a need for more research on sediment connectivity (Section 5.4.2). Therefore, broader (and more 'upstream') approaches for measuring success are currently taken, for example, mapping landslide scars and comparing vegetated slopes to unvegetated slopes. Survival audits have been completed for several years in the Greater Wellington Region on erosion prone land (based on Land Use Capability classification) and the information derived from these audits have enabled planners and planters to be better informed when making planting decisions, to maximise survival. Overall, there is a general reliance on past research in understanding the effectiveness of poplar planting and measuring success. This research is valuable yet can only be applied theoretically to regions or situations outside of the research context. Reference to research and literature developed from historic events such as Cyclone Bola, was mentioned more than once.

5.1.1.3 Planting techniques

The advice on planting technique appears similar between councils and regions; pole drivers/pole bars are used in all regions, but the tool and technique used for the establishment of the guide-hole varied between regions. Contractors in the Wellington region tend to use crowbars or similar implements, which are easier to carry around the hillside and form a smaller guide hole so that the soil can be tightly packed around the base of the pole. The other regions use augers of varying widths. Additionally, in relation to planting techniques and survival, the experience of the planter was considered to be important. GWRC utilise experienced contract planters and therefore do not consider planting technique to be a major cause of poplar death in the region. This was illustrated in the planting trial (Section 4.2.1.1) which showed no pole losses during the trial period for the Wairarapa site, which was planted by professional contract planters. Contrastingly, the Hawkes Bay region largely relies on farmers and landowners to plant poles and

consequently poplar survival is identified as a problem. This was also evidenced in the planting trial results (Section 4.2.1.2 and Section 4.2.1.3) which showed the highest number of pole deaths at sites that weren't contractor planted and were planted by novice planters (i.e., Hawke's Bay and Taumarunui).

5.1.1.4 Survival factors and planting recommendations

Every step of the growing process has the ability to influence survival and some factors are region specific. However, based on current knowledge and experience from interview participants, there are a range of agreed factors identified as important or very important to be considered during the planning and planting stages to maximise survival, despite regional differences (Section 4.1.4):

1. **Time of year** that poles are being planted. It is important to plant at a time of year when water availability is high during the establishment period and ensuring that poles remain in their dormant stage (i.e., winter) to lessen the impact of breakage of any roots or shoots during planting that can compromise establishment success.
2. **Climate** and particularly rainfall is very important to survival. Regions that frequently experience summer drought conditions require a comprehensive understanding of when poplars must be planted to ensure that they capture adequate rainfall before drought conditions commence.
3. **Topography** (e.g., slope gradient). This factor is crucial to the initial planning stage when determining where the trees will be planted and includes avoiding planting in areas that have steep slope angles and thus are more likely to have minimal soil depth and poor water availability.
4. **Position in the landscape** with regard to micro-topography (e.g., small depressions) and quality of planting. Smaller depressions will aid in water availability on hillslopes, it will also encourage planting in areas with good soil depth. Quality of planting suggests the need of an experienced planter to adequately identify these spots. This is where the use of experienced contractors, such as those in the Wellington region is beneficial, instead of relying on farmers/landowners.
5. **Poplar varieties** and consideration of their strengths and limitations. Ensuring poplar varieties are being planted in areas to which they are well suited
6. **Presence of stock and pests**. There was an overall consensus that the removal of cattle for several years after planting (i.e., best practice) is the ideal situation. If cattle cannot be removed, there is a need for adequate protection. It was suggested that the management and condition of the stock (i.e., weight and animal health concerns

such as lice) will aid in the successful establishment of poplar poles by reducing rubbing and grazing.

In challenging terrain with steep slope angles, realistic planting sites need to be determined in terms of pole survival. This might require more conservative decisions and a more active search for alternative tree types such as rooted trees, or species that have better drought tolerance. This also requires a high level of competency for the planners and planters and doing the basics (e.g., stock exclusion, correct siting, and planting depth) really well, to get the best chance of high survival.

5.2 Survival and growth of trial planted poplar material

Previous quantitative research on hill country tree survival, typically considered one or two explanatory variables in isolation. For example, stem diameter (Sulaiman et al., 2005), fertiliser inputs (McIvor et al., 2018), and survival across different soil types and the effects of time (Marden & Phillips, 2013). There appears to be no research that considers the impacts of multiple explanatory variables for survival and therefore makes it difficult to make informed, science-based planting decisions, so the research undertaken in the current study aimed to address these gaps. The objective of the trial (Section 1.1) was to determine which key variables influence survival of poplars planted for erosion control in hill country landscapes. Overall, there was high survival across all sites (90.4%), which was surprising, especially for the north-facing Hawke's Bay and Wairarapa sites; the farmers, council staff and planting contractors predicted these north-facing aspects would have low survival. There was slightly higher survival on the south- rather than the north-facing aspect (247 and 231 trees respectively), but the difference was expected to be larger. The highest survival occurred in poles (169 trees), closely followed by unrooted wands (160 trees), and the lowest survival was in rooted wands (149). The unusually high survival is assumed to have been due to unusual summer climate conditions. The trial period occurred during a period of positive Southern Oscillation Index (i.e. La Niña conditions; https://www.ncei.noaa.gov/access/monitoring/enso/soi) and persistently positive Southern Annular Mode (SAM) (https://niwa.co.nz/climate/information-and-resources/southern-annular-mode). Under these conditions, it can be expected that the eastern side of New Zealand's axial ranges typically experiences higher than normal rainfall with less risk of strong drought, while the western side experiences lower than normal rainfall but typically not sufficient to cause prolonged drought. The effects of this are clearly demonstrated by the rainfall analysis presented (Figs 19 and 20, and Table 14).

5.2.1 Wairarapa

There were no 3-m pole losses at the Wairarapa site; it was the only site where highly experienced planting contractors were utilised. There were high numbers of wands (rooted and unrooted) lost to planting shock; these were not planted by planted contractors. Planting shock losses to the wands were determined to not be caused by environmental factors such as topographic or climatic variables. Instead, the losses may have been due to planting technique or animal damage. This was the first trial site to be planted and all wands were planted by the research team who were mostly inexperienced in wand planting. Factors that might have contributed to losses are not planting to an adequate or correct depth or not packing the soil sufficiently around the wand once planted. Adult cattle were excluded from the trial site, but not young cattle. Because of the steep topography, there is a possibility that cattle were able to reach over the tree-guards to graze the shoots of the wands.

5.2.2 Hawkes Bay

The Hawkes Bay site had the highest number of pole losses across all trial sites (4 total). These were mostly lost on the north-facing slope between the first and second measurement (i.e., determined to be caused by environmental factors). Rooted wand losses (2 planting shock; 2 deaths) occurred on the south-facing slope. All cattle were excluded from the Hawke's Bay sites. It is likely this contributed to the lower wand losses than were measured at the other sites.

5.2.3 Taumarunui

Taumarunui had the highest wand deaths of all the trial sites (5 on the south-facing slope; 2 on the north-facing slope). There was no cattle exclusion from either slope at this site, and as it was the last site to be planted, several wands were protected using modified sleeves when the supply of stainless-steel cages ran out. The sleeves were opened and then wrapped around the wands to prevent stock browsing damage but there was no protection from stock rubbing on the wands and sunlight is likely to have been reduced. The wands that had these guards are outlined in Appendix B with their survival status. Damage from animals is the most likely explanation for the poorer survival at this site, but the region also experienced less rainfall than average (Section 4.2.2.2; Table 14) which could have also contributed to lower survival.

5.3 Trial site climate

The on-site climate stations were used to monitor and collect data for the specific conditions experienced at the trial sites. We used the two climate stations per site to evaluate the difference between north- and south-facing aspects. It was then intended to use the CliFlo

climate stations as an indication of the difference between on-site climatic conditions and those recorded in reasonably close proximity (i.e., the importance of assessing micro-climates), additionally it provided a backup, should an on-site station fail to collect data.

The on-site climate stations at the Wairarapa site malfunctioned, so unfortunately did not record accurate rainfall on either the north- or south-facing sites. The reasons for malfunction appear to be related to a combination of insect interference (spiderwebs) and other yet-to-be determined equipment issues.

The north-facing and south-facing aspect comparisons completed at the Hawke's Bay site showed the north-facing aspect received significantly higher solar radiation, as expected for the Southern Hemisphere. In Taumarunui, the solar radiation between the two aspects were not significantly different. This is likely partly caused by the 'north-facing' slope being oriented more north-west than north. The temperature in Hawke's Bay was very similar across both sites which is likely influenced by its low altitude position near the eastern coast of the North Island. In Taumarunui, there was a significant difference between the temperature at each aspect with the southern aspect receiving lower temperatures between mid-December and February. These sites had much higher altitudes and are situated in the Central Plateau which experiences seasonal snow. There was no significant difference between rainfall at either site between aspects, which suggests that aspect does not significantly affect rainfall under the studied rainfall and slope conditions (different slope angles and orientations relative to the prevailing wind may show a different effect).

The 22-year rainfall analyses showed that rainfall was greater than normal during the trial period in Wairarapa and Hawke's Bay and less than normal in Taumarunui (Table 14). The difference between the nearest CliFlo climate monitoring stations and the on-site climate monitoring stations evidenced the technological fault at the Wairarapa site (+452.8mm). These results detailed a small difference in Hawkes Bay (-29.6mm) and in the Taumarunui (+121.4mm). The greater difference seen at Taumarunui could be reflective of the greater distance between the site and the CliFlo station of 12.8km. This was the greatest distance between climate stations of all the sites but was chosen due to its inclusion of the data for the required climatic parameters. The higher rainfall data collected at the CliFlo station is likely due to its higher elevation (457m) compared to the trial sites (approximately 330m) therefore increasing chances of intercepting rainfall. There was slightly more rainfall collected at the trial sites than the CliFlo station, again this is suggested to be influenced by the lower elevation of the CliFlo station (3-m) compared to the trial sites (48m and 116m).

Long-term forecasting would play a crucial role in planting plans if data was accurate and reliable. The El Niño Southern Oscillation (ENSO) and Southern Annular Mode (SAM) are naturally occurring regional climate cycles. While not entirely consistent, ENSO cycles tend to follow a three-to-seven-year cycle. During El Niño phases, especially during positive SAM, the eastern side of New Zealand typically experiences drier conditions and more rainfall on the western side, with the opposite is true for La Niña phases. Although no cycle is the same, it could be recommended to target higher investment into planting eastern parts of the country (especially those areas determined to be at higher risk of non-survival) during La Niña phases (especially with positive SAM), and likewise, in El Niño phases, planting hill country in the eastern parts of New Zealand could be avoided.

5.4 Study limitations and opportunities

A limitation of Study 1 was the relatively narrow range of viewpoints sought from the participant selection. In hindsight, it would have been advantageous to include industry practitioners from different stages of the planting process. Future research could extend the data collected here by also capturing the views of nursery staff, contract planters, and farmers.

The findings that can be drawn from Study 2 are limited by several methodological constraints. The key limitation of Study 2 was the timescale the research was conducted over. Ideally, growth and survival would have been measured over multiple years, and with successive plantings, to see how the plants perform over a number of seasons and under different climate conditions. Instead, only the first year of the trial was within the scope of this thesis, and unfortunately, the climate conditions were a-typical. Likely due to this ‘abnormal’ climate and short duration, there was high survival, which resulted in a very small sample size of losses to evaluate statistically. Part of the research team intend to continue the trial measurements in the following years, which will likely increase the sample size available, to more robustly evaluate the factors controlling survival and growth. With sufficient data, there is potential to produce a spatial survival model, so that planting practitioners can better plan plantings.

The relatively coarse (15-m) resolution of the DEMs used for the morphometric analysis meant that subtleties in topography, potentially important for impacting survival, may not have been adequately accounted for. For example, for one of the sites, 1-m LIDAR data were available, and a comparison of these data with the 15-m data showed a noticeable

difference in topography (compare Fig 5 produced with lidar data with Figs 7 and 9 produced with 15-m DEM). Using higher-resolution topographic data may help to better identify the influence of microtopography on growth and survival.

The unavailability of detailed soil information was another limitation. Soil type identification was primarily done through available S-Map data and communications with regional councils. It was originally planned to do field assessments of the soil, and probe the soil depth at each tree location, but these objectives were abandoned due to time constraints. In future work, it would be useful to undertake a more detailed analysis of the role of soil properties and depth on survival.

The trial was designed, as best as practicable, to have consistent planting conditions between each farm and slope aspect, so that the effects of climate and aspect could be isolated and robustly evaluated. However, some inconsistencies did occur due to the logistical challenges of working in different regions and with different institutions (with access to different resources). As examples, planting material was sourced from different nurseries, planting method and planter experience differed between councils, due to Covid-19 delays and weather. The timing of planting was not consistent between farms, and stock exclusion practices differed between farms. For future trials, it would be optimal to achieve consistency, perhaps by involving all the affected parties in project design from the start of the project, rather than working separately with each.

The findings of Study 1 and Study 2 presented some research interesting opportunities, including the impacts of contract planters on survival, cattle exclusion and advancements in sediment monitoring. Given that only GWRC uses contract planters and the Wairarapa site had the lowest tree mortality, it may be worth undertaking a cost-benefit analysis of using contract planters instead of in-house personnel or farmers. The additional cost may pay for itself through lower tree mortality and better erosion outcomes. However, any decisions should also be underpinned by further mortality data, given the small sample size of the current study. Cattle damage had previously been identified as a factor affecting tree mortality and was reinforced by the interviews in Study 1 and in the measurements taken in Study 2; the site without cattle exclusion (Taumarunui) had the highest poplar deaths. However, Study 1 participants suggested that cattle exclusion carried an economic impact due to loss of grazeable land. A potential solution to this comes from the growing value of carbon forestry. It is possible that the increasing economic incentive to plant trees (due to carbon credits) could balance the costs associated with cattle exclusion and make it more

feasible to exclude cattle. Future research could explore the cost-benefit analyses of cattle exclusion, including its impact on survival under potential carbon credit scenarios. Finally, there is an opportunity for greater on-site or nearby monitoring of sediment in waterways to help link planting success with positive sediment loss outcomes. HBRC discussed a recent NIWA training course that explored adding signatures to sediment. This would aid in determining if sediment has been remobilised within the channel or was introduced from recent erosion processes and allow the identification of areas within catchments that should receive focus for targeted erosional control mitigations.

5.5 Conclusion

Landowners and councils throughout New Zealand are currently spending a lot of time, effort, and resources in planting trees for erosion control. However, there has been a lack of science or rigorous practice guiding this work and therefore variable outcomes have been achieved in terms of survival and sediment loss throughout the country. This research set out to rectify this by documenting and distilling current practice, assessing the current scientific knowledge and understanding and then trialling some of the variables that influence successful plant establishment in practice. Furthermore, sharing past and present knowledge and experience of industry practitioners can facilitate better ways of doing things, it can create a better experience for landowners, and ensures that knowledge is retained and passed on. Quantifying survival variables can assist in successful planting for erosion control by providing effective and accurate information during the planning and planting phases.

Study 1 interviews showed extensive knowledge and experience amongst industry practitioners. The eight most aligned responses (Table 13) formed the planting recommendations (Section 5.1.1.4) which highlighted the importance of timing of planting, climate, topography and siting, poplar variety and stock and pests. These factors were considered to be important or very important for influencing poplar survival by all survey participants. Future research could substantiate these opinions through quantitative methods that assess the impact of these variables (e.g., through new trials or analyses of existing survival data).

Study 2 research showed that there were no significant effects of the morphometric explanatory variables on survival or growth. However, the growth of poplar poles on south-facing aspects was better than those on north-facing aspects. Although we were unable to get high rates of non-survival, the planting trial indicated that in years of higher rainfall, sites on the East Coast of the North Island that are typically at higher risk for tree non-survival, may be able to be successfully established. This would depend on subsequent years' climate, but from this research, it suggests they can survive their establishment year. This reiterates the importance of accurate long-term forecasting in making planting decisions. The research that was undertaken provided an example of a systematic analysis of the cause of death and quantitatively assessed early establishment. There is no current research in New Zealand that provides the same level of analysis for cause of death and so the current findings provide a foundation for future research.

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Appendix A

Survey questions

1. In your view (specifically for your region), what are the most important factors that influence poplar pole survival?

2. When planning plantings on farms, how do you determine where to plant (distribute) poplars poles?

3. Based on your experience, what is the most effective planting techniques to ensure poles survive?

4. Based on your experience, how best can we increase survival rates of poplar poles in more challenging terrain (e.g., shallow soils, steep slopes etc.)?

5. In your opinion, is treatment of highly erodible land using space planted poplar species an effective method?

6. Do you have any further thoughts on existing methods and how to determine whether space planting poplar poles have been successful/effective?

7. In your opinion, how should “success” of pole-planting be measured:

    a) In terms of a reduction in erosion achieved

    b) A reduction in sediment being delivered to waterways

    c) Both of these

    d) Other (please specify)

8. Please rate the follow factors according to their importance in terms of how they affect survival of poles: (no influence, very little influence, some influence, important factor, very important factor)

    b) Time of year poles are harvested

    c) Time of year poles are planted

    d) Duration of time between harvest and planting

    e) Method of watering poles after harvest

    f) Supply of water for poles (e.g., chlorinated, stagnant, pond, creek, anaerobic muddy bottom)

    g) Where on the stem the poles were cut

    h) How the ends are prepared for planting

    i) Size of the pole

j) Transport of poles (wind drying, rough handling, etc.)

k) Consideration of species and limitations of varieties when planting

l) Choice of planting technique

m) Climate and rainfall

n) Topography (e.g., slope gradient, landform)

o) Lithology

p) Soil type

q) Wind exposure

r) Position in the landscape with regard to micro-topography (e.g., small depressions)

s) Presence of stock and pests/sleeves

t) Pests and diseases

u) Weed spray (e.g., thistle spray).

v) Quality of planting (i.e., depth, re-rammed)

w) Length of time between soaking and planting

Appendix B

Table B1: Planting survival counts and percentages across the three planting trial sites and three planting types

Tree type	**Aspect**	**Non-survival**		**Survived Number (%)**
		Planting shock	**Death**	
Wairarapa Site				
Pole	N			26 (100)
Pole	S			32 (100)
Wand	N	5	1	23 (79)
Wand	S	2	1	28 (90)
Rooted	N	4	1	24 (83)
Rooted	S	6	3	21 (70)
Total		**17**	**6**	**154 (87)**
Hawke's Bay Site				
Pole	N	2	4	24 (80)
Pole	S	1		29 (97)
Wand	N	1		29 (97)
Wand	S			30 (100)
Rooted	N			29 (100)

Rooted	S	2	2	25 (86)
Total		**6**	**6**	**166 (93)**
Taumarunui Site				
Pole	N		1	29 (97)
Pole	S		1	29 (97)
Wand	N	1	2	26 (90)
Wand	S	1	5	24 (80)
Rooted	N	2	2	21 (84)
Rooted	S	1		29 (97)
Total		**5**	**11**	**129 (89)**

Table B2: List of wands in Taumarunui that had alternative protection and their survival status

Wand identification	Survival status		
	Planting shock	Death	Survived
TNW21			X
TNW23			X
TNW25			X
TNW26		X	
TNW27			X
TNW28			X
TNR23		X	
TNR28			X
TNR101	X		
TSW01			X
TSW11		X	
TSW12			X
TSW13			X
TSW19			X
TSW20			X
TSW24		X	
TSW29		X	
TSW30		X	
TSR101			X

Table B3: t-Test for mean growth based on north- and south-facing aspects

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	0.35835616	0.58955555
Variance	0.03430559	0.18038856
Observations	73	90
Hypothesized Mean Difference	0	
df	127	
t Stat	-4.64798032	
P(T<=t) one-tail	4.13623E-06	
t Critical one-tail	1.656940344	
P(T<=t) two-tail	8.27247E-06	
t Critical two-tail	1.978819535	