



THE UNIVERSITY OF  
**WAIKATO**  
*Te Whare Wānanga o Waikato*

Research Commons

<http://researchcommons.waikato.ac.nz/>

## Research Commons at the University of Waikato

### Copyright Statement:

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

The thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- Any use you make of these documents or images must be for research or private study purposes only, and you may not make them available to any other person.
- Authors control the copyright of their thesis. You will recognise the author's right to be identified as the author of the thesis, and due acknowledgement will be made to the author where appropriate.
- You will obtain the author's permission before publishing any material from the thesis.

Assessing drivers of plantation forest productivity on eroded versus non-eroded soils on hilly and steep land in eastern North Island, New Zealand: from catchment to regional scale

A thesis  
submitted in fulfilment  
of the requirements for the degree  
of  
Master of Science in Earth Sciences

at the  
University of Waikato

by

**MARIE JOY HEAPHY**



THE UNIVERSITY OF  
**WAIKATO**  
*Te Whare Wānanga o Waikato*

**April 2013**

## Abstract

---

The impacts of soil erosion on forest productivity in a *Pinus radiata* plantation forest were assessed to determine the effects of key soil properties on tree volume. Fifteen plots on soils markedly eroded (truncated) by landsliding were established in a plantation forested catchment (Pakuratahi) comprising mainly hilly and steepland in a dominantly mudstone/sandstone terrain overlain in places with a mantle of pumiceous tephras in Hawke's Bay, eastern North Island, New Zealand. Fifteen control plots were established on non-eroded soils alongside the eroded soils on landslide scars for comparison. Soils within these eroded and non-eroded sites were analysed and associated trees were measured for height and volume. The analyses of 0.1 m of the soil profile within eroded sites, compared with those of non-eroded sites, revealed that soil properties in eroded sites had significantly lower values: total nitrogen (N) 52%, total carbon (C) 47%, total phosphorus (P) 43% and soil organic matter 36% (SOM) (at 99% confidence interval). The C:N ratio, soil pH, and mean soil depth in eroded plots were also significantly reduced (at 95% confidence interval). Trees on the eroded sites had 14% less volume compared with those growing in soils at the non-eroded sites. Regression analysis revealed a significant relationship between tree volume and total C, total N, and SOM at 99% confidence interval and total P at 95% confidence interval.

Total recoverable volume was less in trees from eroded plots. Log quality and value was assessed using Atlas Forecaster. High-quality pruned logs and large unpruned structural grade sawlogs returned smaller volumes from the eroded plots than from the non-eroded plots. Lower-grade sawlogs returned a higher volume in the eroded plots. Total recoverable volume for a 25-year rotation growing on eroded sites was valued at \$68,494 (2013 value) – 9% less than the estimated value from the control plots (\$75,989). Eroded plots yielded 16% less volume from high quality pruned logs which accounted for a reduction in revenue of around \$4,000 per hectare at eroded sites. A reduction in total recoverable revenue was estimated at \$7,500 per hectare on eroded sites.

Erosion scars were measured and the average soil loss was estimated and reported at 0.1 m depth. On average, an eroded plot lost around 277 m<sup>3</sup> of soil. In total, around 415 tonnes of soil had been displaced from all measured eroded sites. Using digital layers orthorectified from aerial photographs, it was estimated that Pakuratahi catchment has erosion scars covering around 12 hectares of a total area of 774 ha. Extrapolating the soil data from the plots to the catchment, it was estimated that 2385 t of the soil profile, 271 t of C, 20 t of N,

and 3 t of P have been displaced from the slopes of Pakuratahi catchment in the last 100 years. Using a non-linear regression model the potential soil loss following an 80- year and a 100- year extreme rainfall event was predicted. Total soil loss in Pakuratahi catchment was estimated to be 2630 t and 7890 t for an 80- year and 100-year event, respectively.

To gain perspective of the value of avoided erosion or erosion mitigation, at a regional scale in Hawke's Bay, areas with terrain attributes comparable to those of Pakuratahi catchment were identified. The area currently under plantation forestry in such landscapes is around 65 km<sup>2</sup>. The conservative estimate of soil loss on unforested land following an extreme rainfall event for this area is up to  $1.69 \times 10^5$  t. Based on the estimated soil loss calculated from Pakuratahi eroded sites, the value of afforestation of these potentially erodible soils is around NZ\$288 per tonne of soil. Afforestation of erodible land provides a valuable ecosystem service through land stabilisation but this service is currently not recognised financially in New Zealand.

## **Acknowledgements**

---

They say it takes a village to raise a child. In the case of supporting a thesis, it takes an army of helpful colleagues, tolerant friends and patient family. My vast army of supporters have been incredibly kind with time and assistance and I would like to thank them all here.

Firstly to my supervisors, Prof David Lowe, Dr David Palmer, Dr Haydon Jones and Dr Gerty Gielen, I have been very fortunate to have had your input into this work. David Lowe has been extremely encouraging and supportive throughout the process. His calm but enthusiastic guidance ensured that the project reached its rightful conclusion. Dave Palmer's 'can do' attitude is remarkable. He saw the need for this research and was able to see beyond obstacles, moving the project forward on occasions when it stalled. Thanks Dave for not giving up. Haydon Jones continues to inspire me with his attention to detail and great work ethic. His guidance through the later stages of the project was invaluable. Gerty Gielen came on board towards the end, when the painful process of writing commenced in earnest. Making sense of another's jottings is not easy so thanks Gerty for taking the time to help untangle my thoughts.

This project was made possible through funding from Future Forest Research and Scion. My general manager, Dr Trevor Stuthridge, has been very encouraging from the start and together with science leader, Dr Peter Clinton, helped me to see the benefits of undertaking this research. Field assistance, project planning and a lot of fun, was provided by Scion colleagues Graham Oliver, Stephen Pearce and Jason Bennett whose collective years of expertise were invaluable. Loretta Garrett not only helped in the field but also became my soil mentor, sharing her vast knowledge of soil properties, helping with interpretation of results and answering many questions during the write up. Rob Brownlie was very helpful, teaching me the ins and outs of using the Trimble GPS. Mark Kimberley, our resident statistician– I thank you, for always finding time to help even when you were drowning in work. Dr Peter Beets another busy scientist, helped to clarify the project plan and interpret the results. Thanks also go to Dr Richard Yao and Luke Barry for answering questions around forestry economics and to Carolyn Andersen from forest management for her assistance around permanent sample plot data.

My GIS team here at Scion consists of Andrew Dunningham, Barbara Hock, Duncan Harrison and Stefania Pizzirani. You have all helped in different ways and I'm grateful for your support. Thanks, too, to Sarah Orton from Software engineering for guiding me through the Atlas software. Colleagues, Sean Taylor and Marie Dennis, who know only too well what it is like to juggle an MSc, with working full time and parenting, have been true friends, providing unwavering moral support and practical help. I would also like to acknowledge the cheerful assistance I received from staff in the Veritec lab, the Scion Knowledge centre and the Digital Print centre. There are many more people here at Scion who have helped in varying ways, too many to list but you know who you are and your assistance is gratefully acknowledged.

Without the cooperation of PanPac Ltd, in Hawke's Bay, this project would not have been possible. Brett Gilmore (Forestry and Logistics) has been endlessly helpful, providing access to Pakuratahi forest, maps, sharing his knowledge and answering all my queries. Gaining an understanding of how a forest is managed became clearer after many emails and chats with Brian Garnett. Many thanks to you both.

Finally, my family. John and Joyce Heaphy, my parents, and my brother Grant, have quietly in the background, supported me through my studies, providing accommodation, vehicles, food parcels, cash, holidays and moral support. You guys are gold. I could not have got this far without your encouragement and backing. Jack Heaphy, my son, has had a student mother since he was two years old. Now some 13 years later, he has not yet been put off undertaking tertiary study. Mate, you have been a great support but I'll wait until you leave home before tackling the PhD!

# Table of Contents

---

---

<b>ABSTRACT</b> .....	<b>II</b>
<b>ACKNOWLEDGEMENTS</b> .....	<b>IV</b>
<b>TABLE OF CONTENTS</b> .....	<b>VI</b>
<b>LIST OF FIGURES</b> .....	<b>IX</b>
<b>APPENDICES</b> .....	<b>IX</b>
<b>LIST OF TABLES</b> .....	<b>X</b>
<b>CHAPTER ONE: INTRODUCTION</b> .....	<b>1</b>
1.1 BACKGROUND .....	1
1.1 <i>Soil erosion</i> .....	1
1.2 <i>Forest productivity</i> .....	3
1.2 SITE DESCRIPTION .....	6
1.2.1 <i>Catchment characteristics</i> .....	6
1.2.2 <i>Geology</i> .....	8
1.2.3 <i>Soils</i> .....	9
1.2.4 <i>Vegetation</i> .....	10
1.2.5 <i>Climate</i> .....	10
1.2.6 <i>Soil erosion history</i> .....	10
1.3 AIMS AND OBJECTIVES .....	12
1.3.1 <i>Thesis layout</i> .....	13
1.4 REFERENCES.....	14
<b>CHAPTER TWO: IMPACTS OF SHALLOW LANDSLIDE EROSION ON THE PRODUCTIVITY OF <i>PINUS RADIATA</i> PLANTATION FORESTRY, HAWKE'S BAY, NEW ZEALAND</b> .....	<b>17</b>
2.1 INTRODUCTION .....	17
2.2 MATERIALS AND METHODS .....	18
2.2.1 <i>General site description</i> .....	18
2.2.2 <i>Site selection</i> .....	21
2.2.3 <i>Data collection</i> .....	23
2.2.4 <i>Laboratory measurements</i> .....	24
2.2.5 <i>Statistical analysis</i> .....	24
2.2.6 <i>Prediction of growth: Forecaster modelling</i> .....	25
2.3 RESULTS .....	26
2.3.1 <i>Tree growth</i> .....	26
2.3.2 <i>Soil properties</i> .....	26
2.3.3 <i>Soil properties and tree volume</i> .....	27
2.3.4 <i>Effect on recoverable volume and log value</i> .....	28

2.4 DISCUSSION .....	29
2.4.1 Productivity .....	29
2.4.2 Soil organic matter .....	31
2.4.3 Soil phosphorus .....	31
2.4.4 Soil nitrogen .....	32
2.5 CONCLUSIONS .....	33
2.6 REFERENCES .....	34

**CHAPTER THREE: ESTIMATING SOIL AND NUTRIENT LOSSES IN THE  
PAKURATAHI FOREST FOLLOWING EROSION .....38**

3.1 INTRODUCTION .....	38
3.1.1 Background.....	38
3.1.2 Site description .....	38
3.1.3 Monitoring.....	39
3.1.4 Models and classification .....	42
3.1.5 Objectives .....	42
3.2 METHODS .....	43
3.2.1. Geospatial data.....	43
3.2.2. Plot identification .....	43
3.2.3 LiDAR.....	44
3.2.4 Models and classification .....	45
3.3 RESULTS .....	45
3.3.1 Field data.....	45
3.3.2 LiDAR and modelling .....	46
3.4 DISCUSSION .....	49
3.4.1 Erosion.....	49
3.4.2 Soil nutrients.....	50
3.4.3 Risk assessment.....	51
3.5 CONCLUSIONS .....	51
3.6 REFERENCES.....	53

**CHAPTER FOUR: REGIONAL EFFECTS OF EROSION ON FOREST  
PRODUCTIVITY FOLLOWING EXTREME RAINFALL EVENTS HAWKES BAY  
.....57**

4.1 INTRODUCTION .....	57
4.2 METHODS .....	59
4.2.1 Study site description.....	59
4.2.2 Desk-top study .....	59
4.2.3 Field study .....	60
4.2.4 GIS and economics .....	60
4.3 RESULTS .....	61
4.4 DISCUSSION .....	63
4.5 CONCLUSIONS .....	66
4.6 REFERENCES.....	67

<b>CHAPTER FIVE: CONCLUSIONS.....</b>	<b>77</b>
5.1 INTRODUCTION.....	77
5.2 SUMMARY AND CONCLUSIONS .....	77
5.2.1 <i>Impacts of shallow landslide erosion on forest productivity</i> .....	77
5.2.2 <i>Estimating soil and nutrient loss in Pakuratahi</i> .....	78
5.2.3 <i>Regional effects on forest productivity following extreme rainfall events</i> .....	78
5.3 FURTHER RESEARCH .....	79
<b>APPENDIX A .....</b>	<b>80</b>
SOIL PROFILE PAKURATAHI: SCARP WALL BETWEEN ERODED AND NON-ERODED PLOT .....	80
<b>APPENDIX B .....</b>	<b>83</b>
SOIL PROFILE PAKURATAHI: WITHIN ERODED PLOT .....	83
<b>APPENDIX C .....</b>	<b>86</b>
SOIL PROFILE PAKURATAHI: NON ERODED CONTROL PLOT .....	86

# List of Figures

---

---

## Chapter 1

- 1.1 Distribution of *Pinus radiata* in New Zealand, (adapted from LCDB3, 2008)
- 1.2 The 300 Index across New Zealand (Palmer *et al.*, 2010)
- 1.3 Pakuratahi sub-catchment containing fifteen paired plots and slips
- 1.4 Geology – Pakuratahi catchment (Adapted from NZLRI Spatial Data layers (Newsome *et al.*, 2008)
- 1.5 Soil orders: Pakuratahi catchment. (Adapted from NZLRI, (Newsome *et al.*, 2008)
- 1.6 Pakuratahi catchment with slip history
- 1.7 Trial sub-catchment showing mapped slips occurring after major storm events in 1938 and 1988

## Chapter 2

- 2.1 Pakuratahi catchment, situated north of Napier, in the Hawke’s Bay Region, North Island, New Zealand (created using Arc GIS 10.1)
- 2.2 Soil orders, Pakuratahi catchment, adapted from NZLRI (Newsome *et al.*, 2008)
- 2.3 Maps illustrating the fifteen paired plots selected for eroded and adjacent non eroded plots located in first rotation *Pinus radiata* in upper Pakuratahi catchment, Hawkes Bay
- 2.4 Soil profiles for three sites in Pakuratahi Forest

## Chapter 3

- 3.1 Mapped erosion over fifty years in Pakuratahi Forest. Adapted from digital layers (Fransen & Brownlie, 1995)
- 3.2 Non-eroded terrain in Pakuratahi forest
- 3.3 Eroded terrain of similar aspect and slope forming pair
- 3.4 Non-linear regression model
- 3.5 NZLRI erosion classification (Newsome *et al.*, 2008). Erosion severity Classification (Bloomberg *et al.*, 2011)

## Chapter 4

- 4.1 Hawke’s Bay region outlining forest growing on Pallic and Pumice soils overlaying sandstones on slopes over 21°

## Appendices

---

---

- Figure A1 Soil profile described in Typic Immature Pallic Soils
- Figure B1 Soil profile described in Typic Tephric Recent Soil
- Figure C1 Soil profile described in the Weathered Orthic Recent Soil

# List of Tables

---

---

## Chapter 1

- 1.1 Types of erosion, adapted from (Lynn et al., 2009) LUC survey handbook, 3rd edition (pp. 22, 138, 139, 140)

## Chapter 2

- 2.1 Domestic Log Grades, MAF, 2011
- 2.2 A 4th Quarter and 12-Quarter Average as at: December 2012, (MAF, 2011)
- 2.3 Mean tree growth properties - paired sample two tailed t-test
- 2.4 Soil properties – paired sample two tailed t-test
- 2.5 Summary of relationships between soil properties and Pinus radiata tree volume
- 2.6 Log grades and production processes (Pine Manufacturers, 2013)

## Chapter 3

- 3.1 Land use with associated extreme rainfall events adapted from (Fransen & Brownlie, 1995; Harrison et al., in press)
- 3.2 Summary of erosion scar measurements (n = 14) at study plots
- 3.3 Estimated soil and soil nutrient losses from erosion events in Pakuratahi to a depth of 0.1 m
- 3.4 Predicted slip and stability values for an 80- and a 100-year storm event
- 3.5 Estimated soil and nutrient loss using the NLRM model for an 80 year and 100 year extreme rainfall event
- 3.6 Erosion susceptibility and prediction areas

## Chapter 4

- 4.1 Aerial photographs of Pakuratahi used for mapping soil slips and land use with associated extreme rainfall events
- 4.2 Slope class, NZLRI (adapted from Newsome et al., 2008)
- 4.3 Areas of terrain attributes that correspond with those found in Pakuratahi
- 4.4 East Coast Forestry Project Grant rates (MPI, 2010)

# Chapter One: Introduction

---

## 1.1 Background

New Zealand is situated on the obliquely converging boundary of the Australian and Pacific tectonic plates leading to fast rates of uplift and active landsliding and erosion in many parts of the country. New Zealand was heavily forested prior to the arrival of human beings (~85% forest coverage). Early Polynesians began clearing the land using fire soon after arrival ca 1280 AD (McGlone & Wilmshurst, 1999; Wilmshurst *et al.*, 2008; McWethy *et al.*, 2010). With the marked increase in European immigrants from the mid-1800s onwards, large-scale land clearances were carried out, initially in the 1840s-1870s and then expanded from the 1870s to 1920 to acquire land for pastoral farming (McGlone, 1983). Over 22,500 square kilometres of forest was destroyed between 1890 and 1900. Steeper erosion prone slopes subjected to heavy rainfall experienced accelerated erosion as a result (National Water and Soil Conservation Authority (NWSCA, 1985). The Soil Conservation and Rivers Control Council was established in 1941 to promote sustainable land management and soil conservation, primarily to protect lowland communities from flooding and increased sedimentation following large-scale storm-induced soil erosion in hill country and steep-land catchments (especially in the 1930s and 1940s) (Gibbs & Raeside, 1945; Grange & Gibbs, 1947). In the South Island of New Zealand, uplift and erosion rates are so high that man-accelerated erosion is not significant. However in the North Island the rates of uplift are lower so anthropogenic accelerated erosion is considerably higher (Adams, 1980).

### *1.1 Soil erosion*

Soil evolution or pedogenesis involves soil formation and geological erosion. Over time, this process reaches equilibrium with the formation of mature soils. When the land is disturbed by anthropogenic activities such as deforestation, cultivation or overgrazing the process becomes known as accelerated erosion (NWSCA, 1985). Soil erosion can be classified into four groups: surficial, mass movement, fluvial and deposition although often there is cross over between groups (Table 1.1).

Table 1.1 Types of erosion, adapted from Lynn *et al.* (2009), LUC survey handbook, 3<sup>rd</sup> edition (pp. 22, 138,139, 140).

<b>Category</b>	<b>Erosion Type</b>	<b>Definition</b>
Surface erosion	Sheet	Dislodgement and overland flow of surface soil particles by water
	Wind	Detachment and transportation of soil particles by saltation (bouncing along surface)
	Scree	Transportation of rock debris
Mass Movement	Soil slip	Rapid slides and flows involving soil and regolith (usually < 1 m deep)
	Earthflow	Slow movement of soil and regolith along marginal shear planes (rates <0.5 m yr <sup>-1</sup> to > 25 m yr <sup>-1</sup> )
	Slump	Deep seated rotational slide movement containing large blocks of rock and regolith
	Rock fall	Abrupt free fall masses of rock from steep slopes and cliffs
	Debris avalanche	Rapid slides or flows on long steep slopes (occur on >25° slopes)
	Debris flow	Fluid mixtures of debris (rock, soil, vegetation) as a result of landslides triggered by extreme rainfall
Fluvial Erosion	Rill	Closely spaced channels resulting from uneven removal of surface soil by running water (<60 cm and < 30 cm wide)
	Gully	Removal of soil, regolith or rock by fluvial incision (>60 cm deep and >30 cm wide)
	Tunnel gully	Formed by subsurface concentration and flow of water resulting in eluviation and scouring
	Streambank	Removal of streambank material following elevated streamflow
Deposition	Deposition	Sediment that has been eroded, transported and deposited by running water

Soil erosion is influenced by lithology and soil, terrain, landuse, vegetation and climate (Selby, 1993; Pimentel *et al.*, 1995; Lal, 2001). Much of North Island's hill country is covered with shallow tephra-derived soil. The underlying lithology consists of Tertiary and Cretaceous marine sedimentary rocks, mudstones and sandstones. Many hectares of indigenous forest in Hawke's Bay were cleared and, when combined with intense rainfall events, experienced increased soil erosion (Crozier, 1986; Page *et al.*, 1994; Glade, 1998). Soil or earth slip erosion is common in the east coast hill country of the North Island. Earth slip consists of a slide or flow of soil and subsoil that results in a slip surface exposed at a level of more than one metre below the original surface. Following prolonged or heavy rain over a short period of time, a soil may be weakened as water fills the spaces between soil

particles, forcing them apart. Slopes become unstable as shear stress, the force that promotes movement, exceeds shear strength or the ability to resist movement. As the soil weakens and loses resistance, gravity transports the soil down the slope (NWSCA, 1985; Crozier, 1986). Shallow soil slips generally remove much of the soil profile which includes organic matter and the A and upper B horizons. Soil may be lost through sedimentation downstream or by deposition within the same land unit. The eroded surface, subject to rapid weathering can release nutrients and become viable for plant growth (Blaschke *et al.*, 2000) but the removal of the soil profile up to 1 m depth generally leads to a decline in land productivity resulting from degraded soil structure, a decrease in plant nutrients, decreased organic matter and soil fertility, decreased plant rooting depth and altered available water capacity (Lal, 1987). The impact of erosion on the reduced productive capacity of land is increased where subsurface rock is exposed. Mass movement erosion affects 44% of the North Island and 30% of the South Island, in New Zealand (Eyles, 1983).

### *1.2 Forest productivity*

In erosion prone areas plantation forests were planted to stem erosion and to utilise marginal lands. New Zealand commercial forestry is a profit-driven industry requiring productive forests to meet shareholder expectations. A productive forest is defined as one which produces the maximum yield of biomass during a given period of time (Dyck & Skinner, 1990). Productivity is a function of site quality and management practices. Site quality is underpinned by macro-climate and soil properties which contribute to the capacity of a site to produce forest biomass (Dyck & Skinner, 1990). In New Zealand, *Pinus radiata* (*P. rad*) is grown in plantations across a range of edaphic and environmental conditions from latitude 46° 25' 16" and longitude 169° 27' 26" in the South Island to latitude 34° 33' 43" and longitude 172° 50' 40" in the North Island (Fig. 1.1).

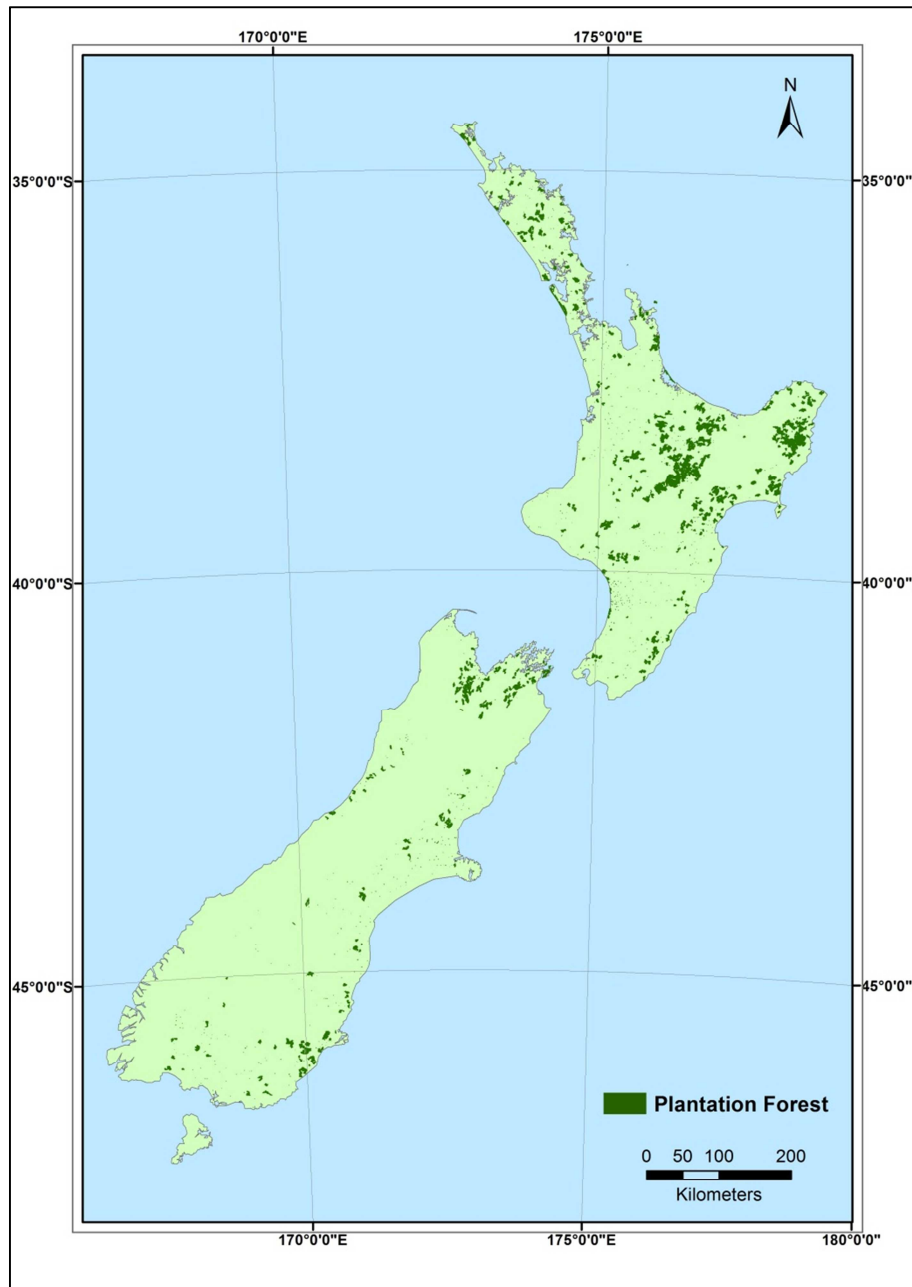


Figure 1.1 Distribution of *Pinus radiata* in New Zealand, adapted from LCDB3, 2008

Management practices incorporate site preparation, fertilisation, genetically improved stock, and harvesting and residue management. Site preparation varies depending on topography and soil conditions. Mechanical preparation such as site ripping is employed to open up compacted soils and increase drainage. Weeds and scrub may be cleared by hand or by using chemicals. Land subject to successive crop rotations may be fertilised to maintain long term sustainability and genetic improvement can influence disease resistance, growth, and form. The productivity of a plantation forest can also be adversely affected by pests, disease and loss of soil nutrients (McLaren, 1993).

Productivity in *Pinus radiata* plantations in New Zealand is quantified by two indices: the 300 Index and the Site Index. The 300 Index defines the stem volume mean annual increment (MAI) at age 30 years for a reference regime of 300 stems ha<sup>-1</sup> (Kimberley *et al.*, 2005). The Site Index defines the mean top height of the 100 largest diameter stems within a hectare at age 20 years (Goulding, 2005). Although widely used, the Site Index is only able to provide a partial measure of site productivity. This is because plantation age and stocking rates impact on basal area growth. The 300 Index measures productivity based on stem volume growth rate (Kimberley *et al.*, 2005). Land supporting higher index figures is more predominant in the North Island (Fig. 1.2).

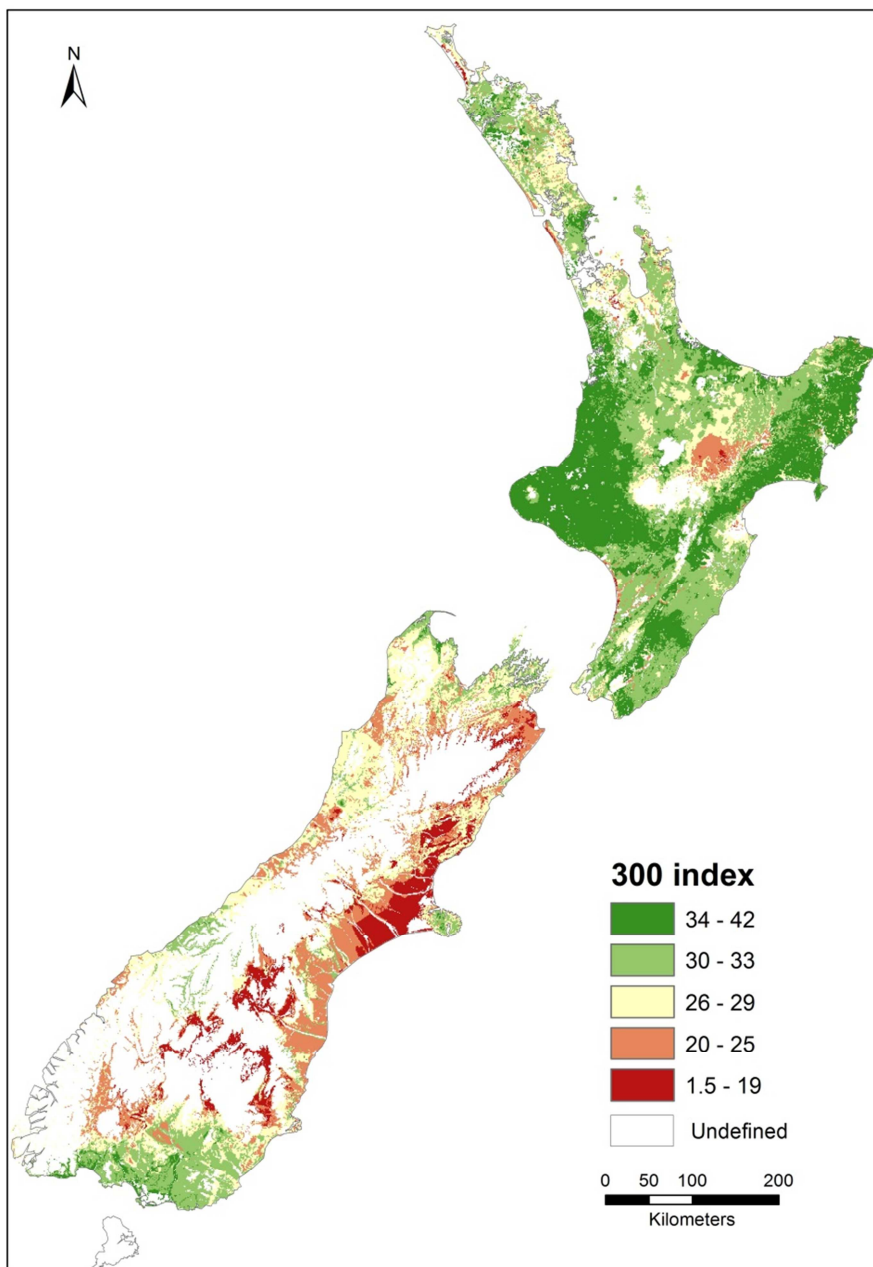


Figure 1.2 The 300 Index across New Zealand (Palmer *et al.*, 2010)

In addition to producing quality timber, New Zealand's foresters have a requirement to report on sustainable forest management, using criteria and indicators outlined in the Montreal Process. Soil erosion is a key indicator and while the ability of trees and forests to protect against erosion has been well documented, there is an increased susceptibility of land to erode post harvesting and during road building (O'Loughlin, 2005). To date, few studies have been carried out on the effect of erosion on productivity in post-erosion forest land.

## 1.2 Site Description

### *1.2.1 Catchment characteristics*

Pakuratahi catchment is located in the Tangoio Forest 21 km northwest of Napier at latitude 39° 20' 57" and longitude 176° 52' 30" (Fig. 1.3). The forest is managed by PanPac Forest Products Ltd, in central Hawke's Bay, NZ.

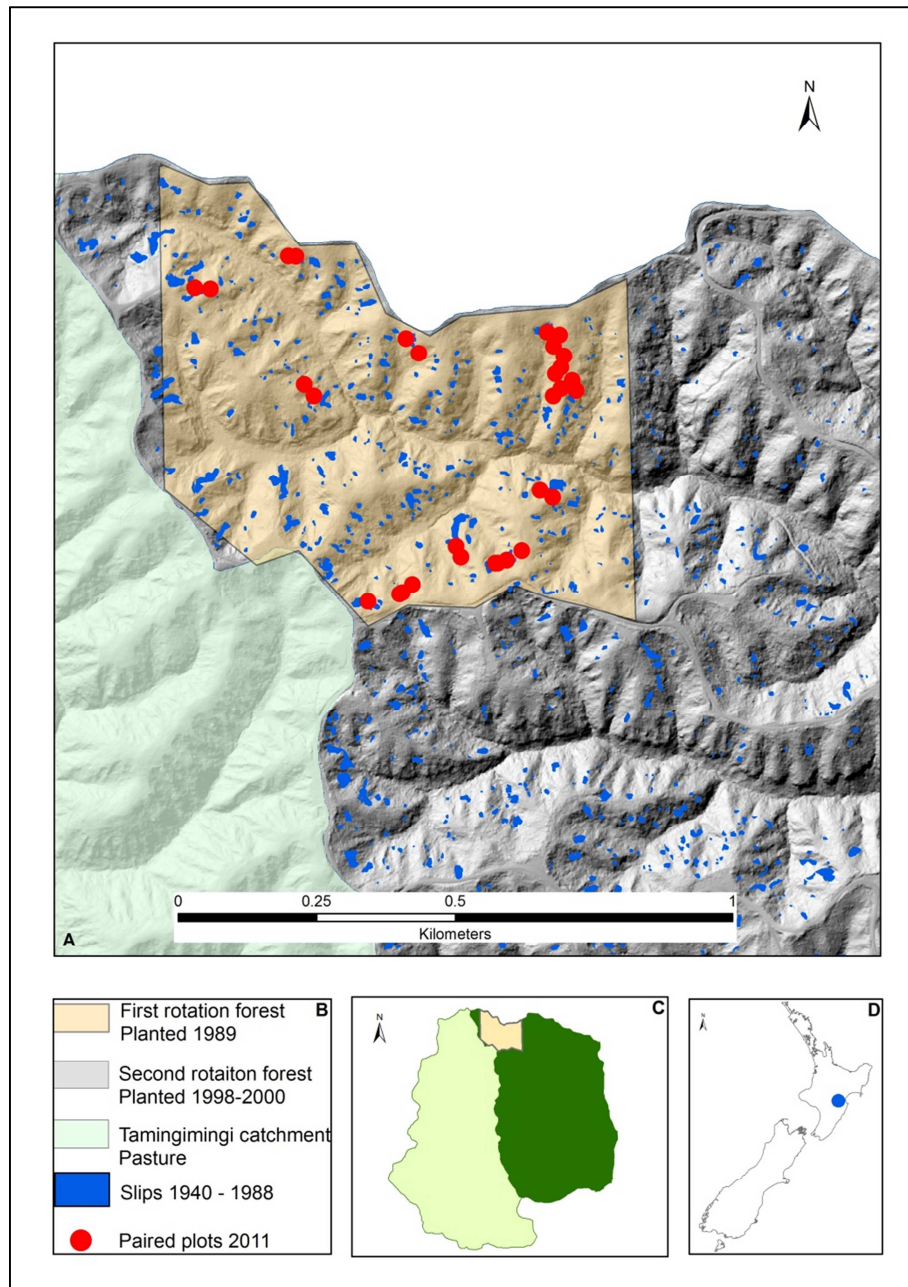


Figure 1.3: (A) Pakuratahi sub-catchment containing fifteen paired plots and slips; (B) Legend for A (C) Trial site in relation to Pakuratahi (dark green) and Tamingimingi (pale green) catchments: (D) inserts show the Pakuratahi forest location in New Zealand. Map created using Esri ArcMap 10.1, DEMs from local LiDAR data (24 August 2011) and historical slip data (Fransen & Brownlie, 1995).

The catchment covers an area of 774 ha and mainly comprises hilly to steep land (over 60% of the catchment contains slopes of 20° or more) with flat to moderately rounded hill or ridge tops, and narrow terraces in valleys in the southern catchment. Elevations range from 18 m to 355 m above sea level (asl) (Eyles & Fahey, 2006).

### 1.2.2 Geology

The main geological formation underlying the Pakuratahi catchment is the Kaiwaka Formation, an early Pleistocene unit aged between 1.6 and 1.77 Ma (million years old) (Bland *et al.*, 2007; Lee *et al.*, 2011). The upper boundary forms the current landscape and erosion surface. Reflecting a multi-depositional environment, the deposits primarily resulted from inner shelf sedimentation, but were also subject to marine and fluvial deposition and rhyolitic tephra fall (Haywick *et al.*, 1991). Digital data from Land Information Resource Services (LRIS) (Newsome *et al.*, 2008) describe the underlying rock as predominantly sandstone with some mudstone in the northwest of the catchment (Fig. 1.4).

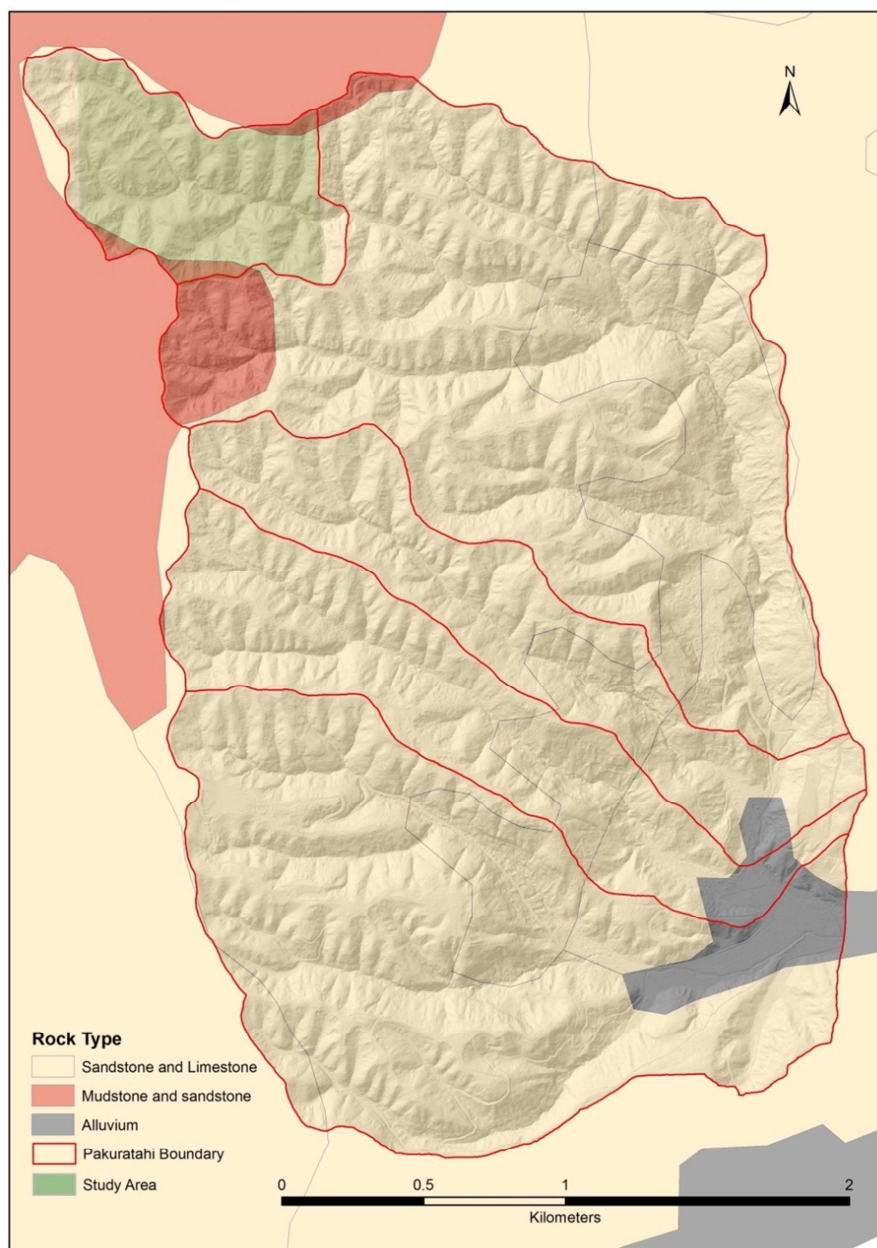


Figure 1.4 Geology – Pakuratahi catchment (adapted from NZLRI Spatial Data layers: Newsome *et al.*, 2008).

### 1.2.3 Soils

Soils in the Pakuratahi catchment are formed primarily from parent materials of mudstone and sandstone and in places from tephras (derived from volcanoes in the Taupo Volcanic Zone) deposited over the sedimentary rocks. Soils on the steep slopes tend to be relatively young because of frequent erosion and are therefore influenced by parent material – commonly exhumed or nearly exhumed after an erosion event – than soils on more stable slopes. In the New Zealand Land Resource Inventory (NZLRI) (Newsome *et al.*, 2008) the main catchment soils are identified as Pallic and Pumice soils (Fig. 1.5).

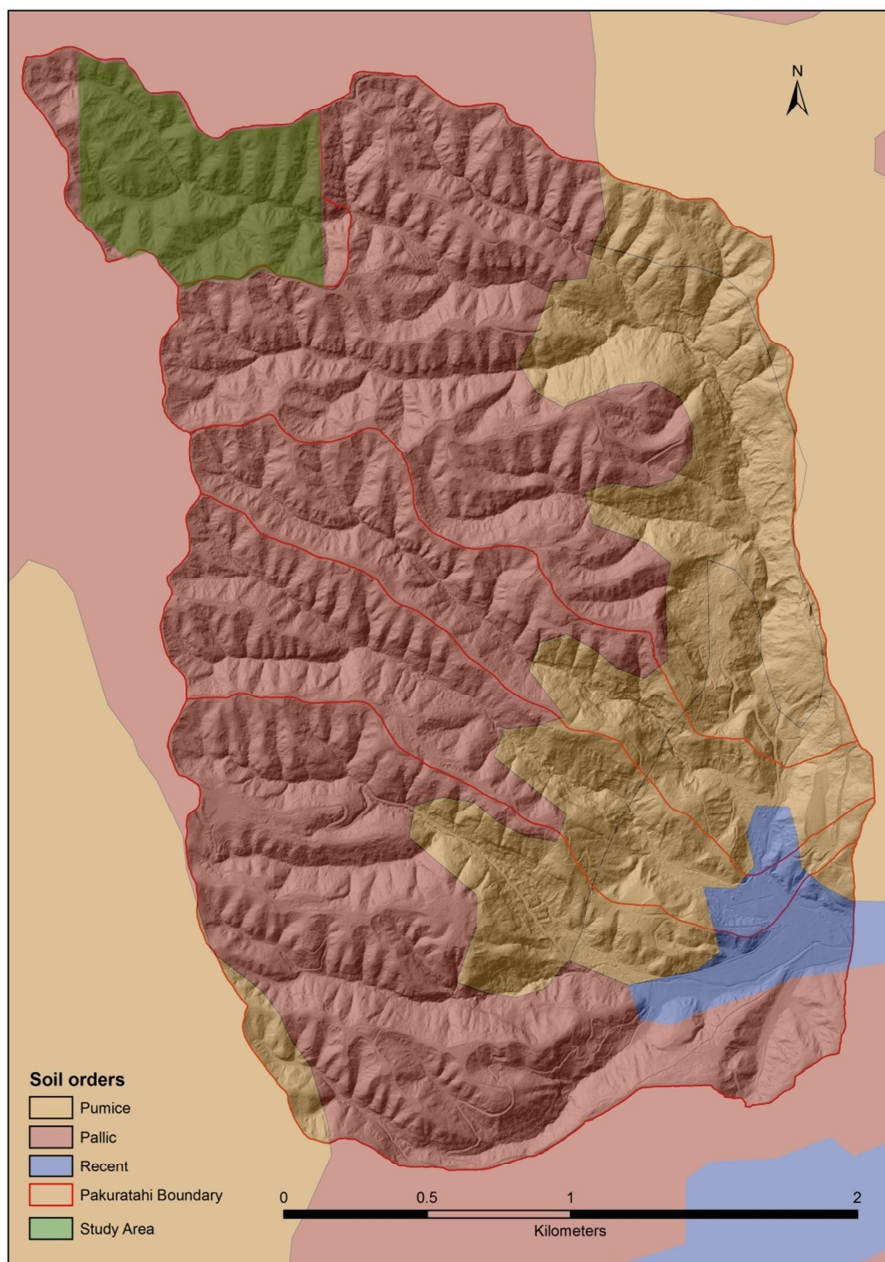


Figure 1.5 Soil orders: Pakuratahi catchment (adapted from NZLRI, Newsome *et al.*, 2008).

#### 1.2.4 Vegetation

The Pakuratahi catchment was originally covered in indigenous forest and in the late 1900s was converted from indigenous forest into pasture for stock grazing. With few improvements made to the pasture, much of the catchment later reverted to scrub. In 1970, most of the catchment was planted in *Pinus radiata* and the first harvest was completed in 1998 (Eyles & Fahey, 2006). The sub-catchment within the Pakuratahi forest where this research was undertaken was first planted in *P. radiata* in 1989.

#### 1.2.5 Climate

The climate across the east coast of New Zealand is variable, experiencing high intensity rainstorms from northern tropical cyclones and cold southerlies from Antarctica (Salinger & Mullan, 1999). In high country areas, total annual rainfall can exceed 2400 mm on approximately 150 days per year when westerly winds prevail. Snow showers are also frequent in winter months. Westerly winds depositing rain in the hills leads to insufficient moisture and drought on the Hawke's Bay plains (Thompson, 1987). Annual rainfall for the region averages around 1043 mm and ranges from 560 mm to 1950 mm. In the hill country, it has been estimated that more than 250 mm of rainfall in a 24 hour period can cause widespread erosion in hill country with minimal vegetation cover (Page, 1994).

Weather data collected at Tangoio 5 km north of the catchment record a mean annual rainfall of 1501. Mean annual temperature is 13.3 °C (February 18.0°C and July 8.4°C) (Eyles & Fahey, 2006). In March 1988, tropical Cyclone Bola caused extensive damage throughout New Zealand. Over 753 mm of rain was recorded during a four day period initiating widespread landsliding in hill country pastureland (Page *et al.*, 1994). Large quantities of sediment were deposited into flood waters and onto the plains causing around 90 million dollars of damage to the local farming and horticultural industries (McSaveney, 2009). Most of the Pakuratahi catchment contained mature first rotation *P. radiata* at the time and consequently suffered minimal damage. However, the small catchment where this project took place was not planted until 1989 and experienced fresh erosion.

#### 1.2.6 Soil erosion history

In Land Use Capability classification, taken from the New Zealand Land Resource Inventory (NZLRI), the Pakuratahi catchment is classified as 6e5 and 7e3, describing moderate to severe limitations to use under pasture and forestry because of erosion susceptibility (Lynn *et*

*al.*, 2009). Historical soil erosion of the area was mapped using a chronological series of aerial photographs taken from 1943 to 1994 using an analytical stereoplotter linked to GIS software (Fransen & Brownlie, 1995) (Fig. 1.6).

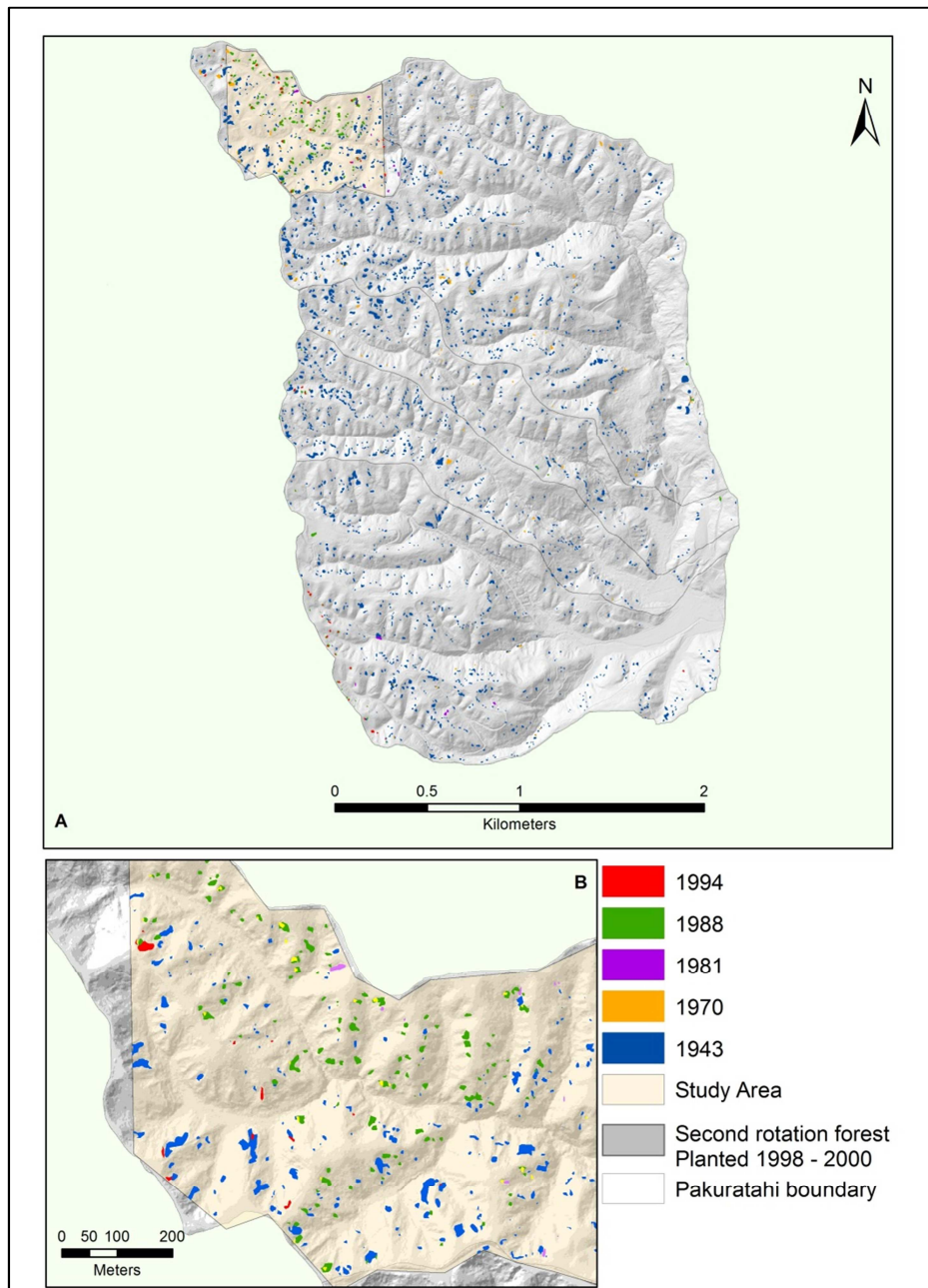


Figure 1.6 (A) Pakuratahi catchment with slip history. (B) Study area in the north of Pakuratahi

Layers derived from orthorectified photographs as follows:

Mar 1943: Erosion after April 1938 storm

Nov 1970: Conditions prior to forest planting

Oct 1981: Forest cover in Pakuratahi catchment

Dec 1988: Erosion after Cyclone Bola in March

Jan 1994: Prior to harvest of first rotation

Minimal new erosion occurred in the Pakuratahi catchment between 1943 and 1987. However, following Cyclone Bola in 1988 an increased area of erosion was recorded in the study catchment which was under pasture when the storm struck (Fig. 1.7.). The remainder of Pakuratahi which was under first rotation forestry at the time, experienced little damage, gaining protection from the 18-20 year old trees.

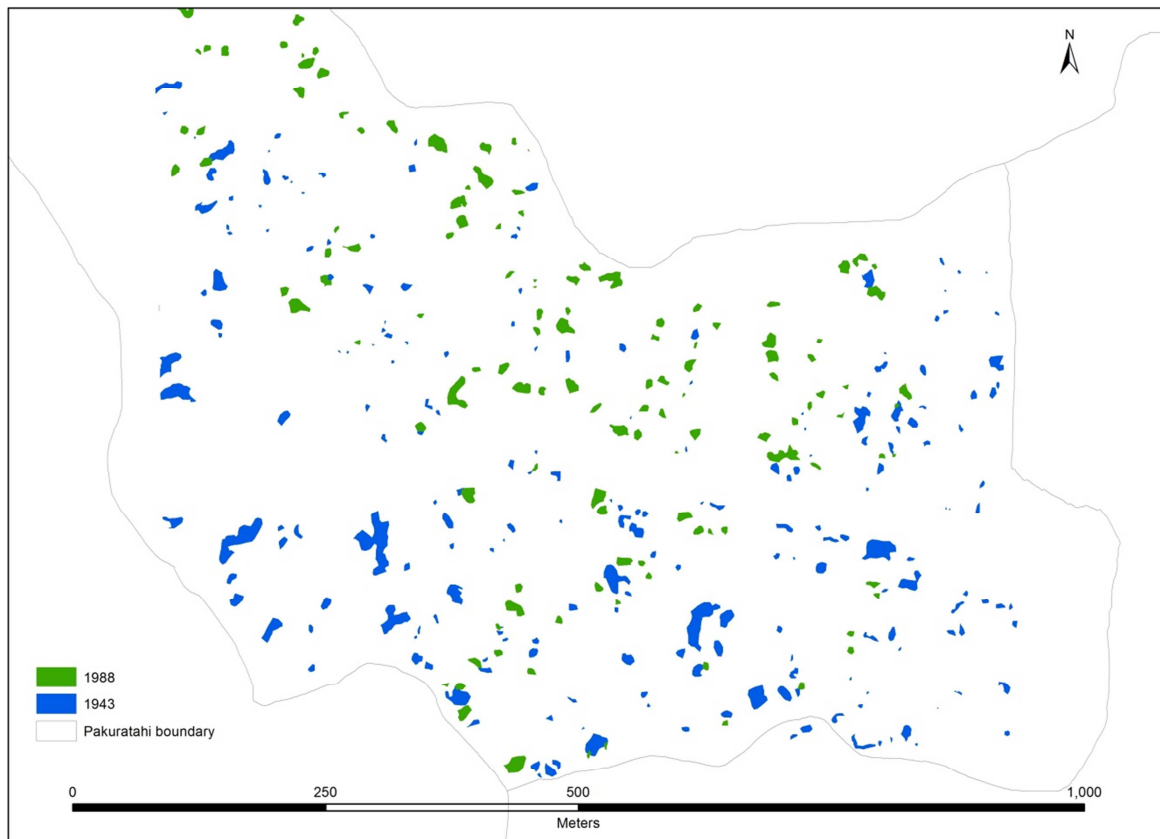


Figure 1.7 Trial sub-catchment showing mapped slips occurring after major storm events in 1938 and 1988.

### 1.3 Aims and Objectives

The overall aim of this research was to investigate the impacts of soil erosion on forest productivity in *Pinus radiata* plantation forestry on the east coast of the North Island, New Zealand.

The three main objectives were set to achieve this aim:

1. Determine the difference between soil properties in eroded and non-eroded land in a sub catchment of Pakuratahi forest and whether this affected forest productivity (Chapter 2)

2. Estimate soil and nutrient loss at catchment scale (Chapter 3)
3. Investigate the potential for reduced productivity across Hawke's Bay region in plantation forest planted post Cyclone Bola (Chapter 4)

### *1.3.1 Thesis layout*

Chapter 1: Introduction and general overview

Chapter 2: The process used to collect soil and forest data from slipped and non-slipped plots is described. The resulting analysis is used to establish a relationship between soil and nutrient loss and forest productivity.

Chapter 3: Digital surfaces are used in a GIS to estimate the loss of soil and nutrients from the study area. These results are extrapolated to include the Pakuratahi catchment. Future soil loss in Pakuratahi following extreme rainfall events is estimated using an empirical nonlinear regression model.

Chapter 4: The potential implications for reduced productivity in Hawke's Bay plantation forests that were planted after the 1988 Cyclone Bola and the costs of avoided erosion to forestry are discussed.

Chapter 5: A summary, conclusions, and recommendations for further research are presented. Because chapters 2 to 4 are written in the form of scientific papers, there is some unavoidable overlap between them.

## 1.4 References

- Adams, J. (1980). Contemporary uplift and erosion of the Southern Alps, New Zealand. *Geological Society of America Bulletin*, 91(2), 115.
- Bland, K. J., Kamp, P. J. J., & Nelson, C. S. (2007). *Systematic Lithostratigraphy of the Neogene succession exposed in central parts of Hawke's Bay Basin, eastern North Island, New Zealand*. Ministry of Economic Development New Zealand Unpublished Petroleum Report PR3724.
- Blaschke, P. M., Trustrum, N. A., & Hicks, D. L. (2000). Impacts of mass movement erosion on land productivity: A review. *Progress in Physical Geography*, 24(1), 21-52.
- Crozier, M. J. (1986). *Landslides: causes, consequences and environment*. New Hampshire, USA: Croom Helm.
- Dyck, W. J., & Skinner, M. F. (1990). *Potential for Productivity Decline in New Zealand Radiata Pine Forests*. Paper presented at the Sustained Productivity of Forest Soils Conference, University of British Columbia, Vancouver, British Columbia.
- Eyles, G. O. (1983). The distribution and severity of present soil erosion in New Zealand. *New Zealand Geographer*, 39(1), 12-28.
- Eyles, G.O., Fahey, B.D. (2006). Introduction. In: G.O. Eyles, B.D. Fahey (Eds.), *The Pakuratahi Land Use Study. A 12 year paired catchment study of the Environmental effects of Pinus radiata Forestry, Hawke's Bay Regional Council*.
- Fransen, P., & Brownlie, R. (1995). Historical slip erosion in catchments under pasture and radiata pine forest, Hawke's Bay hill country. *NZ Forestry*, (November), 29-33.
- Gibbs, H. S., & Raeside, J. D. (1945). Soil erosion in the High Country of the South Island: *New Zealand Department of Scientific and Industrial Research, Bulletin 92*.
- Glade, T. (1998). Establishing the frequency and magnitude of landslide-triggering rainstorm events in New Zealand. *Environmental Geology*, 35(2-3), 160-174.
- Goulding, C. J. (2005). Measurement of trees. In M. Colley (Ed.), *NZIF Forestry Handbook* (4th ed ed.). Christchurch, New Zealand: New Zealand Institute of Forestry.
- Grange, L. I., & Gibbs, H. S. (1947). Soil erosion in New Zealand. Part 1. Southern half North Island. *New Zealand Soil Bureau Bulletin 1*.

- Haywick, D. W., Lowe, D. A., Beu, A. G., Henderson, R. A., & Carter, R. M. (1991). Pliocene-Pleistocene (Nukumaruan) lithostratigraphy of the Tangoio block, and origin of sedimentary cyclicity, central Hawke's Bay, New Zealand. *New Zealand Journal of Geology & Geophysics* 34, 213-225.
- Kimberley, M., West, G. G., Dean, M. G., & Knowles, R. L. (2005). The 300 index – a volume productivity index for radiata pine. *New Zealand Journal of Forestry*, 50, 13-18.
- Lal, R. (1987). Effects of soil conservation on crop productivity. *Critical Review of Plant Science* 5, 303-367.
- Lal, R. (2001). Soil degradation by erosion. *Land Degradation & Development* 12(6), 519-539.
- Landcare Research. (2013). Landcover database 3, National Land Resource Centre. from <http://www.nlrc.org.nz/home>
- Lee, J.M. Townsend, D., Bland, K., Kamp, P.J.J. (compilers). (2011). Geology of the Hawke's Bay area: scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences Limited. Institute of Geological & Nuclear Sciences 1:250,000 geological map 8.1 sheet + 93 p.
- Lynn, I. H., Manderson, A. K., Page, M. J., Harmsworth, G. R., Eyles, G. O., Douglas, G. B., Mackay, A. D., & Newsome, P. J. F. (2009). *Land Use Capability Survey Handbook - a New Zealand classification of land, 3rd ed.* AgResearch Lt, Hamilton; Landcare Research New Zealand Ltd, Lincoln; Institute of Geological and Nuclear Sciences Ltd, Lower Hutt.
- McGlone, M. S. (1983). Polynesian deforestation of New Zealand: A preliminary synthesis. *Archaeology in Oceania* 18, 11-25.
- McGlone, M. S., & Wilmshurst, J. M. (1999). Dating initial Maori environmental impact in New Zealand. *Quaternary International* 59, 5-16.
- McLaren, J. P. (1993). *Radiata Pine Grower's Manual FRI Bulletin No. 184*. Rotorua: New Zealand Forest Research Institute Ltd.
- McSaveney, E. 'Floods - Southland floods and Cyclone Bola', Te Ara - the Encyclopedia of New Zealand, updated 13 July 2012 from <http://www.TeAra.govt.nz/en/floods/page-4>

- McWethy, D. B., Whitlock, C., Wilmhurst, J. M., McGlone, M. S., Fromont, M., Li, X., Dieffenbacher-Krall, A., Hobbs, W. O., Fritz, S. C., & Cook, E. R. (2010). Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. *Proceedings of the National Academy of Sciences of the United States of America* 107, (50) 21343–21348.
- National Water and Soil Conservation Authority (NWSA). (1985). Resources for the future: New Zealand's National Water and Soil Conservation Survey. Wellington, New Zealand.
- Newsome, P. F. J., Wilde, R. H., & Willoughby, E. J. (Eds.). (2008) Land Resource information system spatial data layers. Palmerston North, New Zealand: Landcare Research.
- O'Loughlin, C. (2005). The protective role of trees in soil conservation. *New Zealand Journal of Forestry*, 49 (4) 9-15.
- Page, M. J., Trustrum, N.A., DeRose, R.C. (1994). A high resolution record of storm induced erosion from lake sediments, New Zealand. *Journal of Paleolimnology* 11, 333-348.
- Page, M. J., Trustrum, N. A., & Dymond, J. R. (1994). Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand. *Geomorphology* 9, 169-188.
- Palmer, D. J., Watt, M. S., Kimberley, M. O., Hock, B. K., Payn, T. W., & Lowe, D. J. (2010). Mapping and explaining the productivity of *Pinus radiata* in New Zealand. *New Zealand Journal of Forestry* 55, 15-21.
- Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, R., Saffouri, R., & Blair, R. (1995). Environmental and economic costs of soil erosion and conservation benefits *Science* 267 (5201), 1117-1123.
- Salinger, M. J., & Mullan, A. B. (1999). New Zealand climate: temperature and precipitation variations and their links with atmospheric circulation 1930-1994. *International Journal of Climatology* 19, 1049-1071.
- Selby, M. J. (1993). *Hillslope Materials and Processes*, 2nd ed. New York: Oxford University Press.
- Thompson, C. S. (1987). The climate and weather of Hawke's Bay. Series 115 (5) New Zealand Meteorological Service, Wellington.
- Wilmhurst, J. M., Anderson, A. J., Higham, T. F. G., & Worth, T. H. (2008). Dating the late prehistoric dispersal of Polynesians to New Zealand using the commensal Pacific rat. *Proceedings of the National Academy of Sciences of the United States of America*, 105, 7676-7680.

# **Chapter Two: Impacts of shallow landslide erosion on the productivity of *Pinus radiata* plantation forestry, Hawke's Bay, New Zealand**

---

## 2.1 Introduction

Erosion by mass movement is a common form of soil loss in steepland and hill country in New Zealand. The New Zealand archipelago is bisected by an active, obliquely converging boundary of the Australian and Pacific lithospheric plates. Together with climatic impacts (including frequent rainstorms), the ensuing dynamic tectonism contributes to very fast rates of denudation (landsurface lowering) through active erosion. Most of New Zealand was forested (c. 85% cover) prior to partial clearance through burning following the arrival of Polynesians late in the 13<sup>th</sup> Century, and faster land clearances by European farmers subsequently (from the mid- to late-19<sup>th</sup> Century on) to acquire land for pastoral farming (McGlone, 1983; McGlone & Wilmshurst, 1999; Newnham & Lowe, 1999; McWethy *et al.*, 2010). Over 22,500 km<sup>2</sup> of native forest was destroyed between AD 1890 and 1900 in New Zealand. Over time much of the indigenous forest across the Hawke's Bay in eastern North Island was converted to pasture. Under intense rainfall events increased landsliding and soil erosion occurred in the region (Crozier, 1986; Page *et al.*, 1994; Glade, 1998).

Mass movement in the form of shallow landslides or soil slips generally results in the removal of much of the soil profile which includes organic matter, the top soil, and upper subsoil. Soil may be lost through sedimentation downstream or may be deposited within the same land unit. The eroded surface, subject to rapid weathering, may be able to release nutrients and hold sufficient moisture to become viable for plant growth (Blaschke *et al.*, 2000) but the removal of the soil to depths greater than 1-m generally leads to a substantial decline in land productivity as a result of soil structure loss, a decrease in plant nutrients, organic matter and soil fertility, decreased plant rooting depth, and altered available water capacity (Lal, 1987). It has been estimated that of the 20% of the world's land area subjected to periodic mass movement activity, nearly half of this area is used for land-based production, including forestry (Blaschke *et al.*, 2000) A large proportion of erosion research carried out in the USA, has focused on the surface effects on cultivable land, but there is little documented research into the effects of mass movement on plantation forests and agroforestry (Blaschke

*et al.*, 2000). Mass movement is less likely to occur under forest, and long harvest cycles require long term trials to determine effects of erosion on productivity. Using eroded and non-eroded (control) paired plots (n=15) across a 23 year old *Pinus radiata* plantation the objectives of this study were to determine the impact of soil physical and chemical properties on *Pinus radiata* productivity, and investigate the economic impact of any difference.

## 2.2 Materials and Methods

### 2.2.1 General site description

The Pakuratahi forest catchment is situated 21 km north of Napier, Hawke's Bay, at latitude 39° 20' 57" and longitude 176° 52' 30" (Fig.2.1) and is managed by PanPac Forest Products Ltd. The Hawke's Bay region experiences a variable climate with summer droughts and high intensity rainfall. Mean annual rainfall ranges from 440 mm to 1300 mm with maximum daily rainfall ranging from 28 mm to 300 mm (NIWA, 2010). Mean annual temperature at Tangoio, 5 km north of the catchment, is 13.3 °C (Eyles & Fahey, 2006).

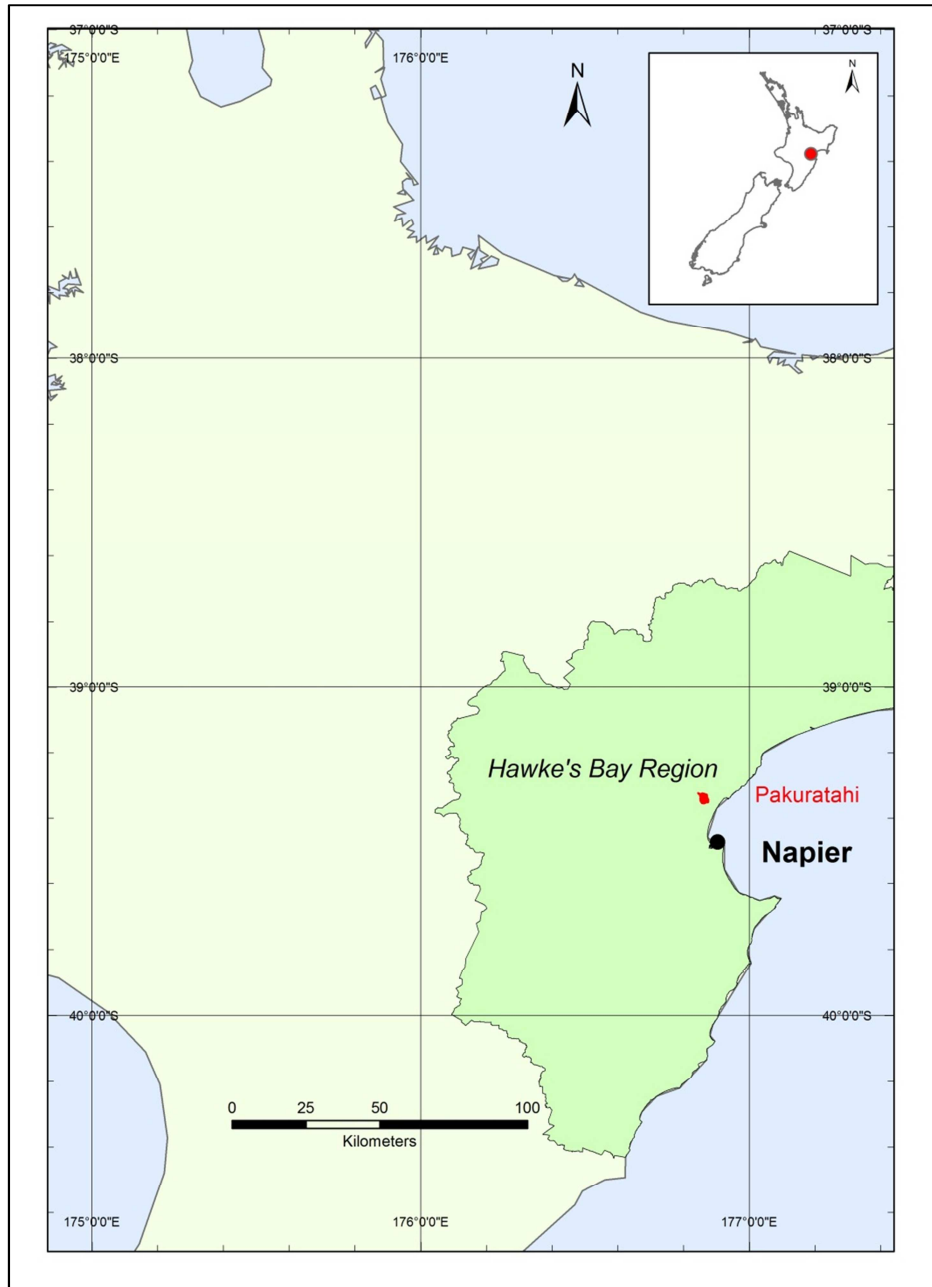


Figure 2.1 Pakuratahi catchment situated north of Napier, in the Hawke’s Bay Region, North Island, New Zealand (created using Arc GIS 10.1).

Covering 774 ha, the Pakuratahi catchment is mainly comprised of hilly to steep land (over 60% of the catchment contains slopes of 20° or more) with flat to moderately rounded hills or ridge tops, and narrow terraces in valleys in the southern section of the catchment. Elevation ranges from 18 m to 355 m above sea level. The main geological formation underlying the Pakuratahi catchment is the Kaiwaka Formation, an early Pleistocene sedimentary unit aged between 1.6 and 1.7 million years old and up to 100 m thick. Reflecting a multi depositional environment, the formation primarily resulted from inner shelf sedimentation, but was also subject to marine and fluvial deposition and rhyolitic tephra fall (Haywick *et al.*, 1991).

Found mainly on the upper ridges and steep slopes, tephric soils developed *in situ* on the Taupo Tephra Formation (c. 1500 yrs BP) and the Waimihia Tephra Formation (c. 35000 yrs BP) (Froggart & Lowe, 1990). The sandy loam topsoils are commonly 200-400 mm thick, overlaying an eroded surface formed on Kaiwaka Formation sand (Eyles & Fahey, 2006).

The New Zealand Land Resource Inventory (NZLRI) digital database identifies the two main soil orders in the catchment as Pallic and Pumice Soil with a third order in the south of the catchment around the Pakuratahi River containing Recent soils (Newsome *et al.*, 2008) (Fig. 2.2). With the removal of vegetation, soils in the Pakuratahi subjected to extreme rainfall events were more susceptible than those under plantation forestry. Page *et al.* (1993) estimate around 250 mm of rainfall over 2 to 3 days as an approximate threshold to induce significant erosion in the Hawke's Bay hill country. With rainfall data gathered from four stations around Pakuratahi, Fransen and Brownlie (1995) reported around 80 days of rainfall over 100 mm since 1984 and approximately 10 periods of rainfall over 250 mm during the same time.

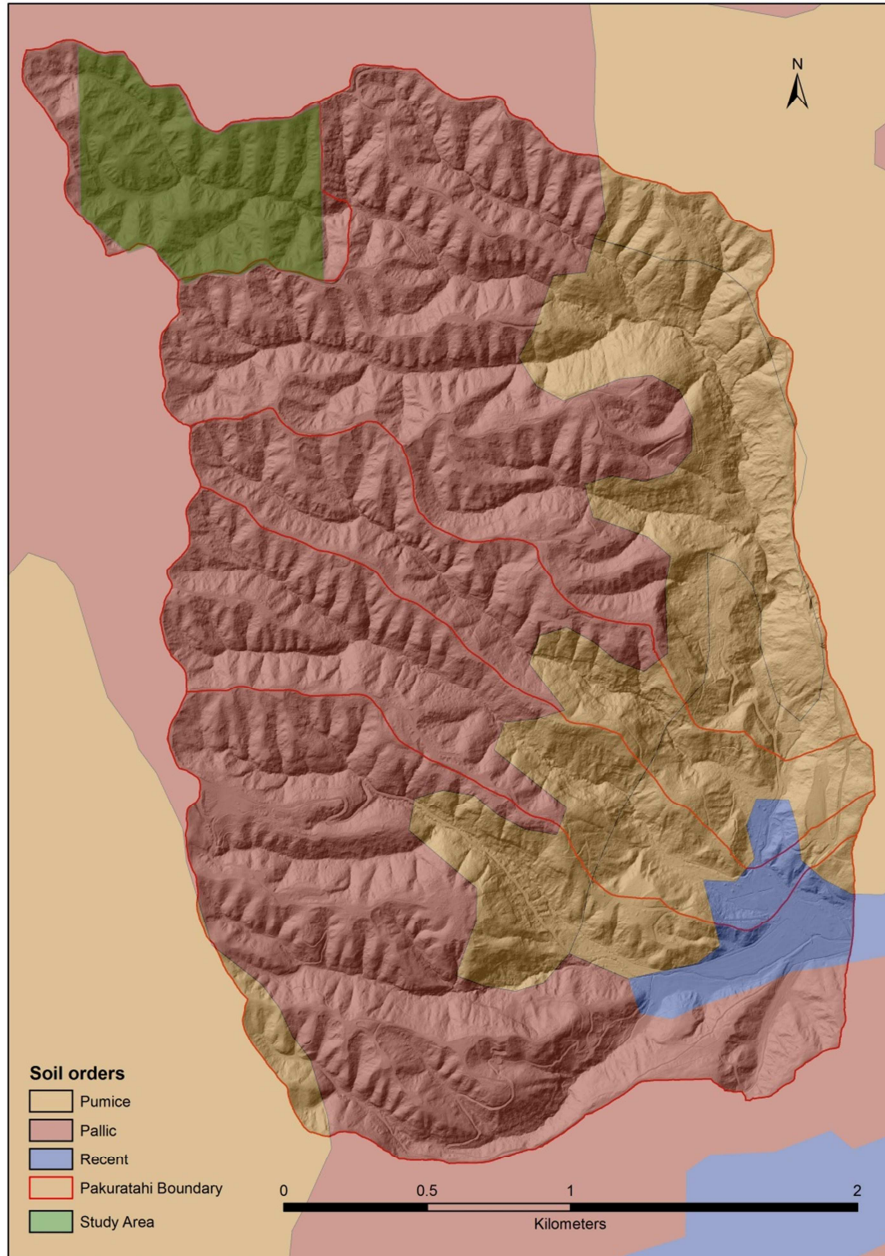


Figure 2.2 Soil orders, Pakuratahi catchment, adapted from NZLRI (Newsome *et al.*, 2008).

### 2.2.2 Site selection

Data from the digitised surface of erosion slips recorded after storm events between 1943 and 1994 (Fransen & Brownlie, 1995) were used to underpin site selection of erosion scars. Erosion scars greater than 0.02 ha were identified as suitable for field examination under the first rotation *Pinus radiata* plantation. Fifteen plots were established within erosion scars and paired with 15 plots located on adjacent non eroded (stable) land of similar aspect and slope (Fig. 2.3).

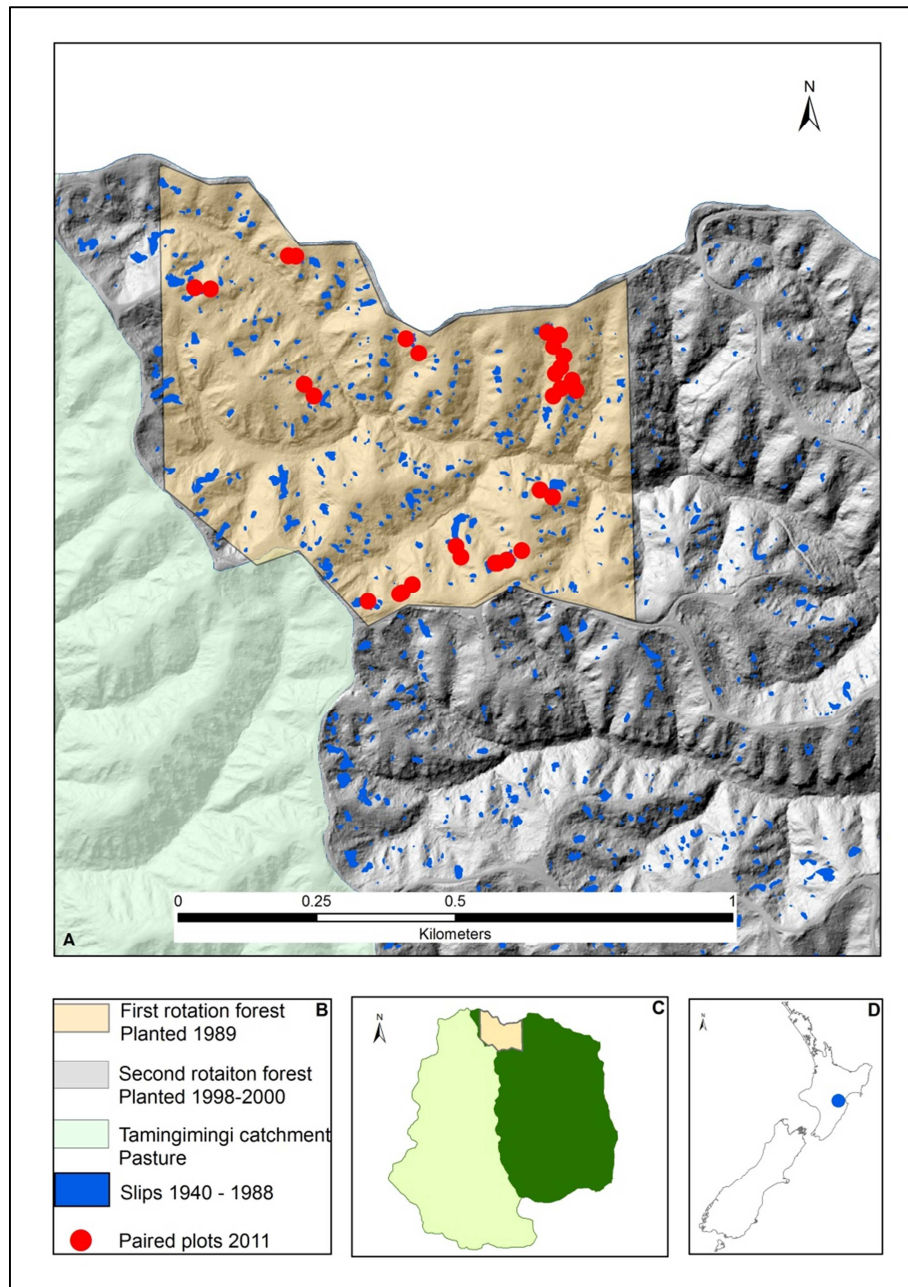


Figure 2.3 Maps illustrating (A) the fifteen paired plots selected for eroded and adjacent non eroded plots located in first rotation *Pinus radiata* in upper Pakuratahi catchment, Hawkes Bay, and map; (B) legend for map A; (C) location of the trial catchment within the Pakuratahi forest (dark green) and neighbouring Tamingimingi pasture (D) research location in the Hawke's Bay (blue enclosed circle), North Island, New Zealand. Maps generated using ESRI ArcMap 10.1

The number of trees per plot ranged from 5 to 10. Although plots varied in slope, size and aspect, care was taken to ensure paired sites had similar terrain attributes and mean basal area was calculated. Plot sizes ranged from 90-127 m<sup>2</sup>, slopes from 10-33°, and aspect from 2 - 358°.

The plot locations were ground-surveyed using a high grade (sub-meter accuracy) Global Navigation Satellite System (GNSS) receiver (a Trimble ProXRT). Using GPS ensured that the plots could be located should pegs be removed and data could be used for mapping into a GIS. The raw data were differentially-corrected using Trimble GPS Pathfinder Office Software (v5.3), a process which accesses the Land Information New Zealand (LINZ) network of base stations to improve survey point accuracy.

### *2.2.3 Data collection*

In each plot, trees were measured for diameter at breast height (dbh) and tree height. Tree form was recorded. Tree form describes tree growth or health such as whether a treetop is dead, defective or forked, is the tree leaning, swept over or toppled but still alive (Ellis & Hayes, 1997). Twenty soil samples per plot were collected for chemical analysis at 0-10 cm depth using a small-diameter (23-mm) tube-sampler. The samples were selected randomly across each plot on a grid basis and were bulked for analysis per plot. At each soil sample extraction site a 10 mm diameter metal probe was inserted into the ground to estimate depth to the contact between solum and the underlying impenetrable layer. Three bulk density samples per plot were collected using metal rings, 98 mm in diameter and 100 mm in length. Samples were collected randomly over the length of each slip. Bulk density samples were bulked for analysis per plot. Using a Dutch auger, six samples were examined per plot to determine the depth of the A horizon.

Three modal pedons (Fig. 2.4: a, b, c) were selected and described within the trial catchment (see appendix A, B and C for full soil description) at a (a) slip side wall, (b) slip central location, and (c) stable site (control plot). Samples for chemical analysis and bulk density measurement were collected in each individual horizon throughout the three soil profiles.

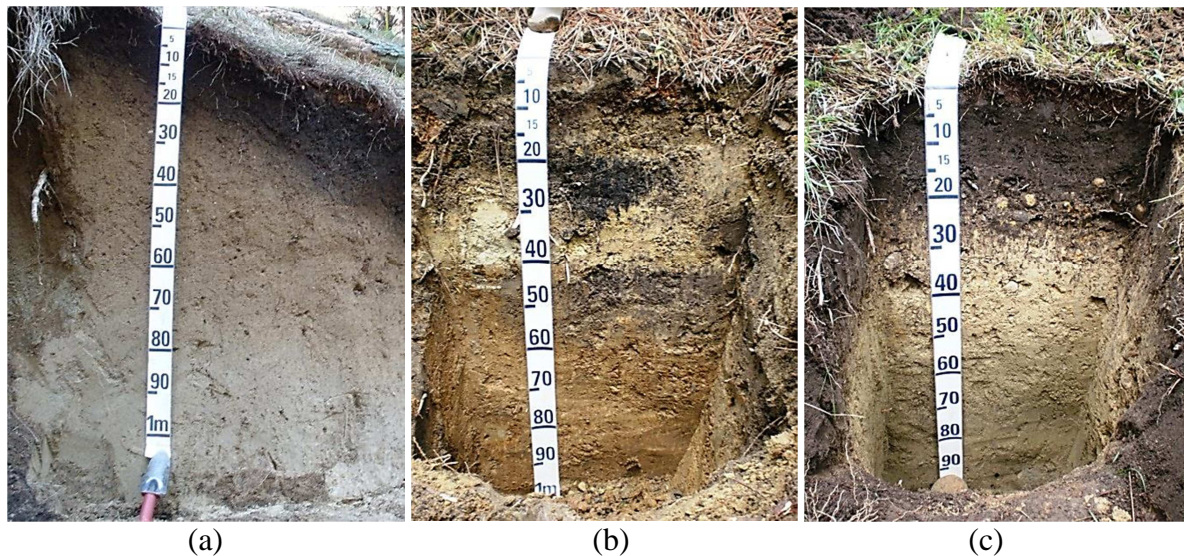


Figure 2.4 Soil profiles for three sites in Pakuratahi Forest on (a) Slip side wall (*i.e.*, eroded soil at unstable site), (b) slip central location (*i.e.*, soil at site that has received deposition material from upslope), (c) stable site (*i.e.*, soil at stable site, neither eroding nor receiving soil deposition). For full soil descriptions, see appendices.

#### 2.2.4 Laboratory measurements

Soil samples for chemical analysis were air dried at 20°C and passed through a 2-mm sieve. Total carbon and total nitrogen were analysed on a LECO CNS-2000 (Modified Dumas). Total phosphorus was measured by Flow Injection Analysis (FIA) colorimetry after sequential Kjeldahl digestion. Phosphorus retention was measured by FIA colorimetry after sequential 1:10 Bray 2 (NH<sub>4</sub>F/HCl) extraction. Soil pH was determined using an electronic probe and a 1:2.5 soil to water ratio solution with distilled water (1:2.5 dH<sub>2</sub>O). Soil organic matter content was measured by loss on ignition at 550°C. Bulk density was determined from oven dry weight of a known volume of the 3 samples. Samples were air dried and sieved to < 2 mm. The < 2-mm fraction and the coarse > 2-mm material were separated. The < 2mm fraction was oven dried at 105°C for 24 hours and then weighed again to determine oven dry weight.

#### 2.2.5 Statistical analysis

Paired *t*-tests for sample means (Microsoft Office Excel, 2007) were used to test for significant differences in soil properties, and average tree size across the eroded and non-eroded sites. Due to the small plot size (constrained by erosion scar size) average tree size across the plots in the catchment was used as a measure of productivity. The 300 index was not used in this instance due to the effect of low stocking numbers on the outcome.

Regression analysis (Microsoft Office Excel, 2007) was carried out to determine any relationships between measured soil properties and tree volumes.

### 2.2.6 Prediction of growth: Forecaster modelling

Growth simulation software, Atlas Forecaster<sup>1</sup>, was used to estimate the economic/return value of the trees measured in this trial. This software enables the determination of the potential revenue loss from trees grown in slip scars compared to trees grown in stable, non-slip areas. Forest mensuration data consisting of tree height, dbh, and tree form, were converted into stem lists and imported into Atlas GeoMaster<sup>2</sup>. PanPac Ltd provided additional silvicultural data including planting dates, stocking, pruning, and clearfell ages. Site location, was set up using co-ordinates in New Zealand Transverse Mercator<sup>3</sup> and altitude information collected in the field using GPS. The data were run through the forecaster model using standard Ministry of Agriculture and Forestry log grades (MAF, 2011) (Table 2.1) for the cutting strategy and default function models specific to the site.

Table 2.1 Domestic log grades, MAF, 2011

<b>Log grade</b>	<b>Log status</b>	<b>Small end diameter (mm)</b>	<b>Maximum knot (mm)</b>	<b>Sweep class</b>
P1	Pruned	400 +	0	1
P2	Pruned	300-399	0	1
S1	Unpruned	400 +	60	1
S2	Unpruned	300-399	60	1
S3	Pruned or unpruned	200-299	60	1
L1	Unpruned	400 +	140	1
L2	Unpruned	300-399	140	1
L3	Unpruned	200-299	140	1
Pulp	Unpruned	100	n/a	2

Log grades were established, determining log volume and value (MAF, 2011) (Table 2.2) for pruned trees, structural timber, utility grade timber, and pulp.

<sup>1</sup> Atlas Forecaster – Growth simulation software (West *et al.*, 2012)

<sup>2</sup> Atlas Geomaster - Forest activity planning and management software. <http://www.atlastech.co.nz/products/geomaster-range/geomaster>

<sup>3</sup> NZTM Mapping Projection defined in terms of NZGD 2000 – New Zealand Geodetic Datum 2000

Table 2.2 A 4th quarter and 12-quarter average as at: December 2012, (MAF, 2011)

<b>Generic log type &amp; pricing point</b>	<b>Dec-12 quarter</b>	<b>12-quarter average</b>
Pruned	144-190	168
Unpruned A Grade	103-125	126
Unpruned K Grade	90-121	116
Pulp	79-102	109
<b>Domestic (NZ\$ per tonne delivered at mill)</b>		
P1	122-149	138
P2	111-123	118
S1	95-104	99
S2	90-97	95
L1 and L2	77-96	88
S3 and L3	77-86	81
Pulp	48-53	51

## 2.3 Results

### 2.3.1 Tree growth

Paired, two tailed *t*-tests were used to determine whether there were significant differences in growth variables, between eroded and non-eroded plots. DBH and volume were significantly higher at 9% and 14% respectively in the non-eroded plots. The difference in tree height was not significant, at less than 1% (Table 2.3).

Table 2.3 Mean tree growth properties - paired sample two tailed *t*-test. P value: \*\*\* p=0.001; \*\* p=0.01; ns=not significant

	<b>Non-eroded</b>	<b>Eroded</b>	<b>% Difference</b>	<b>Probability</b>
Height (m)	35.6	35.9	<1	ns
DBH (cm)	536.3	493.3	9	***
Volume (m <sup>3</sup> )	2.7	2.3	14	**

### 2.3.2 Soil properties

Measured soil properties were significantly less in eroded plots with the exception of bulk density and the mean depth of A the horizon. At 99.9% confidence, total N results showed the biggest difference at 52% less content in eroded plots. At the same confidence level, total C measured 47% less, total P 43 % less and soil organic matter was 36% less in eroded plots. At 95% confidence mean soil depth, C:N ratio and pH were significantly less in eroded plots at 16, 8 and 3% respectively (Table 2.4).

Table 2.4 Soil properties – paired sample two tailed *t*-test – P value: \*\*\* p=0.001; \*\* p=0.01; \*P=0.05; ns=not significant

	<b>Non-eroded</b>	<b>Eroded</b>	<b>% Difference</b>	<b>Probability</b>
Total carbon (%)	3.73	2	47	***
Total nitrogen (%)	0.29	0.14	52	***
C:N ratio	12.9	14	8	*
Total phosphorus (mg kg <sup>-1</sup> )	371	215	43	***
Soil organic matter (%)	8.86	5.71	36	***
Soil pH	5.59	5.47	3	*
Mean soil depth (m)	0.42	0.31	16	*
Mean A horizon thickness (m)	0.23	0.18	12	ns
Bulk density (g m <sup>-3</sup> )	1.09	1.04	5	ns

### 2.3.3 Soil properties and tree volume

Regression analysis was carried out using Microsoft excel 2007, to determine a relationship between decreased soil properties and tree volume. Ratios of slip data over non-slip data were calculated for regression analysis (Table 2.5). Total carbon, nitrogen, phosphorus and soil organic matter all had a significant effect on tree volume. The effects of soil pH, bulk density, soil depth and depth of the soil A horizon were insignificant. Soil properties grouped for multiple regression analysis did not result in any significant relationships.

Table 2.5 Summary of relationships between soil properties and *Pinus radiata* tree volume. P value: \*\*\* p=0.001; \*\* p=0.01; \*P=0.05; ns=not significant

Ratio of eroded vs. non-eroded soil data	Slope	p value	Probability
Total carbon	0.2	0.0154	**
Total nitrogen	0.2	0.0136	**
C:N ratio	-0.4	0.2512	ns
Total phosphorus	0.2	0.0324	*
Soil organic matter	0.24	0.0183	**
Soil pH	-1.7	0.2122	ns
Mean soil depth (m)	-0.3	0.2113	ns
Mean A horizon thickness m)	0.08	0.1537	ns
Bulk density	-0.06	0.8678	ns

#### 2.3.4 Effect on recoverable volume and log value

The returns from a plantation depend on the quality of log that is extracted from a forest. Different quality logs have specific end uses (Table 2.6).

Table 2.6 Log grades and production processes (Pine Manufacturers, 2013)

Log Types	Process and Product Options
Pruned sawlogs (P)	High quality straight logs – appearance grade lumbar
Small branch sawlogs (S)	Structural lumber
Large branch sawlogs (L)	Industrial appearance lumber
Residual logs	Pulp and panel products

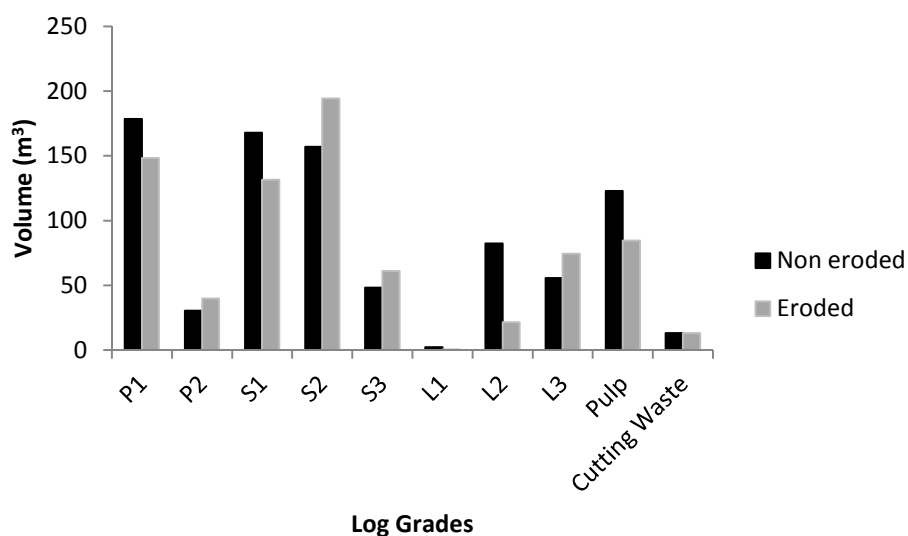


Figure 2.5 Total log volumes per grade in eroded and non-eroded plots for 25 year old trees

Total recoverable volume was lower from eroded plots. High quality pruned logs (P1) and large unpruned structural grade sawlogs (S1) returned smaller volumes from eroded plots than from non-eroded plots (Fig 2.5). However, S2, S3 and L3 grade sawlogs returned a higher volume in the eroded plots. Total recoverable volume for a 25 year rotation growing on eroded sites was valued at \$68,494 – 9% less than the estimated value from the control plots (\$75,989). Eroded plots yielded 16% less volume in high quality pruned logs which accounted for a reduction in revenue of around \$4,000 per hectare at eroded sites. A reduction in total recoverable revenue was estimated at \$7,500 per hectare on eroded sites (Fig. 2.6).

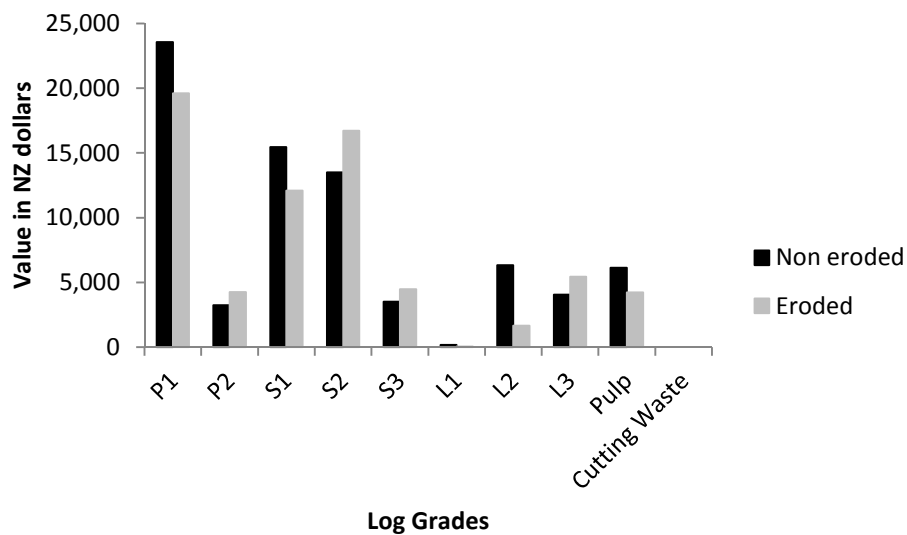


Figure 2.6 Log values per grade in eroded and non-eroded plots **P** = Pruned trees – high quality straight logs; **S** = Unpruned -structural timber; **L** = Unpruned - utility timber; **Pulp** for paper; **Cutting waste** which is left onsite.

## 2.4 Discussion

### 2.4.1 Productivity

Average tree size across the catchment, used as a measure of productivity, showed a significant reduction in volume in eroded plots. However, there was no significant difference in the mean top height between the paired sites. Of the few national and international studies researching the effects of erosion on forest productivity, all found a decrease in tree volume.

In the Pakuratahi catchment, Dean and Heron (1998) examined the forest productivity of first rotation *P. radiata* in 20 paired plots on known eroded and adjacent control sites. A 10%

reduction in mean diameter at dbh was found in the slipped areas in addition to 26% less total stem volume per hectare and a lower yield of more valuable pruned logs. In Queen Charlotte Sounds, British Columbia, 49 landslides ranging in age from 1 to 155 years were surveyed and it was found that the trees on landslides averaging an age of 85 years produced around one half the wood volumes of normal second-growth stands of the same age (Smith *et al.*, 1986). Landslides occurring in natural forests have shown adverse effects on recovery, with reduced rates of biomass accumulation and a different species composition to the surrounding forest on landslide surfaces in Hawaii (Francescato *et al.*, 2001) and in New Hampshire (Restrepo *et al.*, 2003).

Forestry research is supported by pasture studies in New Zealand which found a reduction in productivity following erosion. Trials examining pasture growth of revegetating slip scars, determined that dry matter production on recently eroded sites was depressed by around 80% relative to non-eroded ground. Full recovery is slow and complete recovery is unlikely as a loss in potential pasture production of 2% per decade was predicted, for entire hillslopes where landslides occurred frequently (Trustrum *et al.*, 1983; Lambert *et al.*, 1984; DeRose *et al.*, 1995). Rosser and Ross (2011) determined that soil nutrient status on eroded pastureland recovered to around 75-80% of uneroded sites after 60 years.

*Pinus radiata* is able to withstand a wide range of climatic conditions and environments from dry exposed sites and salt laden air to alpine land up to 500 m above sea level. However, sites overly deficient in macronutrients and experiencing other soil limitations (such as poor drainage) will have a low growth potential (Will, 1985). In this project regression analysis revealed that total carbon, total nitrogen, and soil organic matter contents were significantly correlated to tree volume. Analysis of soils from the paired plots revealed significant difference in total carbon, total phosphorus, total nitrogen, and soil organic matter in eroded plots compared with these properties in control plots. The results are not unexpected because when a shallow landslide or soil slip occurs, up to a metre of soil, encompassing the entire solum can be displaced. The solum includes organic matter and the nutrient-rich A and upper B horizons. In the early stages of tree growth and development, much of the nutrient requirements of growing trees are provided by the mineral soil and are immobilised in the tree's tissues. When canopy closure is reached, the trees become more dependent on nutrient cycling within the forest ecosystem receiving inputs from forest litter and the atmosphere

(McLaren & Cameron, 2005). Turner and Lambert (2011) observed a 25% reduction in basal area in a *P. radiata* plantation following the removal of litter over a 16 year period. Trees in slips are disadvantaged due to the loss of nutrient-rich top soils and are unable to access nutrients via litter until much later in the rotation.

#### 2.4.2 Soil organic matter

Although the C:N ratio was significantly different with an average of 13:1 for eroded plots and 14:1 for controls, soil organic matter tends to stabilise between 8:1 and 16:1 (McLaren & Cameron, 2005) which might explain the lack of correlation between the C:N ratio and tree volume in regression analysis. The C:N ratio is less important in forest soils than soil nitrogen content as trees are able to access soil nitrogen through mycorrhizal symbioses (Woollons *et al.*, 2002). There was a strong correlation between total C, total N, total P and soil organic matter and tree volume. Soil organic matter was significantly less in eroded plots compared to controls ( $P=0.001$ ). Soil organic matter (SOM) content is the mainstay of forest productivity. Depending on environmental factors such as temperature, water, and interactions with other soil properties, SOM can have adverse or beneficial effects on forest productivity (Grigal & Vance, 2000). Variation in soil properties is largely determined by the amount of SOM in a soil (Federer *et al.*, 1993). Soil microbes, decomposing new litter on an eroded site, take up nitrogen, phosphorus, and other nutrients, in mineral form from the existing soil. As decomposition continues, CO<sub>2</sub> is given off to the atmosphere and the requirement for nutrients decreases. However, decomposition of new litter on newly eroded sites can place heavy demands on soils which may be nutrient deficient as a result of lost top and subsoil, leading to slower recovery of SOM (Turner & Lambert, 2011).

#### 2.4.3 Soil phosphorus

A significant relationship ( $P=0.05$ ) between total phosphorus and tree volume was found in this study which has been found in earlier trials in New Zealand. A strong positive correlation between productivity and soil phosphorus levels was found in a trial in a *P. radiata* forest at Riverhead in Northland in northern North Island (Ballard, 1970). In other trials, *P. radiata* growth was found to respond positively to applications of phosphate fertiliser. Phosphorus deficiency is a common limiting factor in plantation forestry. However, an association between radiata roots and ectomycorrhizal fungi can enhance the capacity of *P. radiata* to access forms of P that are not available to other plants, such as soil organic P (Davis & Lang, 1991; Davis *et al.*, 1996). The soils in Pakuratahi, formed from mudstone and sandstone

overlaid by weathered rhyolitic tephtras. These soils tend to be low in total P but have strong buffering capacity (Palmer *et al.*, 2005) which means that phosphorus can be adsorbed on to the surfaces of soil minerals such as allophane and later become available for plant uptake. Analysis of soils throughout the three profiles (Fig 2.3) revealed strong to moderate allophane in the control plot and erosion scar wall soil samples. However, Allophane was absent in the slip profile as a result of the displacement of weathered tephtras. Three Bray 2 extractions (Bray & Kurtz, 1945) were carried out to provide an indication of available P in soil solution and longer term P supply. Each subsequent extraction produced a decreasing but not insubstantial amount of P, reflecting the ability of the Pakuratahi soils to continue to supply P over time in both eroded and the control plots (Palmer *et al.*, 2005).

#### 2.4.4 Soil nitrogen

Studies on soil nutrients in New Zealand plantation forestry have revealed deficiencies in nitrogen and the potential to improve productivity through fertilisation. Early studies carried out on central North Island soils revealed an increase in volume increment of around  $8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  following nitrogen application and on less fertile soils in Nelson responses were up to  $17 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  (Mead & Gadgil, 1978). Will (1971) found that nitrogen deficiencies resulted in reduced branch and stem diameter growth. The soils analysed in Pakuratahi revealed 50% less soil nitrogen in eroded plots than in non-eroded plots.

Soil slip erosion has reduced soil organic matter and nutrient levels which has led to a reduction in diameter in trees growing in eroded plots in Pakuratahi. Amelioration may require targeted fertilisation. In the 1950s routine fertilisation was carried out on forestry land in New Zealand. Early field trials revealed improvements in tree diameter growth in plots treated with superphosphate. Identified soil nutrient deficiencies such as nitrogen, phosphorus, and boron were routinely corrected by fertilisation. However, this practice dropped off by the late 1980s (Will, 1985). Fertilisers are now used where management studies or economic analysis suggest an advantage or to improve long term productivity (Mead & Gadgil, 1995). In Pakuratahi, fertilisation was not included in the management regime for the 1998 rotation of trees where this study took place. A significant reduction in revenue from trees grown in slips in Pakuratahi may lead to select fertilisation programmes in future rotations.

The potential yield of trial trees was analysed using the Atlas Forecaster model which predicted a loss in revenue for trees grown at eroded sites. The difference in value for total recoverable volume was \$7,500 per hectare and around \$4,000 per hectare for high quality pruned logs. Non eroded plots covered an area of 0.27 ha with an estimated return of \$76,000. Pakuratahi forest covers an area of 774 ha. The total area of slips in the entire catchment is 12 hectares, with the potential for around \$900,000 in reduced revenue. Potential return for the entire catchment without the effects of erosion is around 217 million dollars. Whether this justifies the expense of fertilisation depends on current fertiliser and log prices. There is an economically optimal level of erosion where the cost of an extra unit of mitigation is equal to the value of additional erosion costs avoided (Crosson, 1997). Cost benefit analysis could be carried out on this site to estimate the value of mitigation measures.

## 2.5 Conclusions

This study has shown that trees growing on eroded land (*i.e.* on shallow soils that had been eroded due to soil and earth slips) yielded 14% less mean volume than those grown in adjacent control sites, consistent with the findings of an earlier study by Dean and Heron (1998). The key influences on volume increment in the Pakuratahi forest catchment were total carbon, total nitrogen, total phosphorus and soil organic matter. Economic analysis undertaken using Geomaster Forecaster revealed a 9% reduction in total recoverable volume which equated to around \$7500 per ha in reduced revenue from trees grown at eroded sites. Future research may look at the cost of avoided erosion by planting exotic forestry and analyse the costs and benefits of applying fertiliser to this site. Analysis of that nature could be useful to for improving revenue returns.

## 2.6 References

- Ballard, R. (1970). The phosphate status of the soils of Riverhead Forest in relation to growth of radiata pine. *New Zealand Journal of Forestry*, 15(1).
- Blaschke, P. M., Trustrum, N. A., & Hicks, D. L. (2000). Impacts of mass movement erosion on land productivity: A review. *Progress in Physical Geography*, 24(1), 21-52.
- Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic and available forms of phosphorus in soils. *Soil Science*, 59, 39-45.
- Crosson, P. (1997). The on-farm economic costs of erosion. In R. Lal, W. H. Blum, C. Valentin & B. A. Stewart (Eds.), *Methods for assessment of soil degradation*. (pp. 495-511). Boca Raton: CRC Press.
- Crozier, M. J. (1986). *Landslides: causes, consequences and environment*. New Hampshire, USA: Croom Helm.
- Davis, M. R., Grace, L. J., & Horrell, R. F. (1996). Conifer establishment in South Island high country: Influence of mycorrhizal inoculation, competition removal, fertiliser application, and animal exclusion during seedling establishment. *New Zealand Journal of Forestry Science*, 26(3), 380-394.
- Davis, M. R., & Lang, M. H. (1991). Increased nutrient availability in topsoils under conifers in the south island high country. *NZ Journal of Forestry Sciences*, 21, 165-179.
- Dean, M., & Heron, C. (1998). The effect of historical soil erosion on tree quality and volume: Report No. 58. Forest and Farm Plantation Management Cooperative.
- DeRose, R. C., Trustrum, N. A., Thomson, N. A., & Roberts, A. H. C. (1995). Effect of landslide erosion on Taranaki hill pasture production and composition *New Zealand Journal of Agricultural Research*, 38, 457-471.
- Ellis, J.C. & Hayes, J.D. (1997). Field guide for sample plots in New Zealand forests. *Forest Research Institute*, 186.
- Eyles, G.O., Fahey, B.D. (2006). Introduction. In: G.O. Eyles, B.D. Fahey (Eds.), *The Pakuratahi Land Use Study. A 12 year paired catchment study of the Environmental effects of Pinus radiata Forestry*, Hawke's Bay Regional Council.
- Federer, C. A., Turcotte, D. E., & Smith, C. T. (1993). The organic fraction - bulk density relationship and the expression of nutrient content in forest soils. *Canadian Journal of Forest Research*, 23.

- Francescato, V., Scotton, M., Zarin, D. J., Innes, J. C., & Bryant, D. M. (2001). Fifty years of natural revegetation on a landslide in Franconia Notch, New Hampshire, U.S.A. *Canadian Journal of Botany*, 79(12), 1477-1485.
- Fransen, P., & Brownlie, R. (1995). Historical slip erosion in catchments under pasture and radiata pine forest, Hawke's Bay hill country. *NZ Forestry*, (November), 29-33.
- Froggart, P. C., & Lowe, D. J. (1990). A review of late Quaternary silicic and some other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution, volume, and age. *New Zealand Journal of Geology and Geophysics*, 33(1), 89-109.
- Glade, T. (1998). Establishing the frequency and magnitude of landslide-triggering rainstorm events in New Zealand. *Environmental Geology*, 35(2-3), 160-174.
- Grigal, D. F., & Vance, E. D. (2000). Influence of soil organic matter on forest productivity. *New Zealand Journal of Forstry Science*, 30(1/2).
- Haywick, D. W., Lowe, D. A., Beu, A. G., Henderson, R. A., & Carter, R. M. (1991). Pliocene-Pleistocene (Nukumaruan) lithostratigraphy of the Tangoio block, and origin of sedimentary cyclicity, central Hawke's Bay, New Zealand. *New Zealand Journal of Geology & Geophysics*, 34(2), 213-225.
- Lal, R. (1987). Effects of soil conservation on crop productivity. *Critical Review of Plant Science* 5, 303-367.
- Lambert, M. G., Trustrum, N. A., & Costall, D. A. (1984). Effects of soil slip erosion on seasonally dry Wairarapa hill pastures. *New Zealand Journal of Agricultural Research*, 27(1), 57-64.
- McGlone, M. S. (1983). Polynesian deforestation of New Zealand: A preliminary synthesis. *Archaeology in Oceania*, 18(1), 11-25.
- McGlone, M. S., & Wilmshurst, J. M. (1999). Dating initial Maori environmental impact in New Zealand. *Quaternary International*, 59(1), 5-16.
- McLaren, R. G., & Cameron, K. C. (2005). *Soil Science: Sustainable production and environmental protection*. Melbourne, Australia: Oxford University Press.
- McWethy, D. B., Whitlock, C., Wilmhurst, J. M., McGlone, M. S., Fromont, M., Li, X., Dieffenbacher-Krall, A., Hobbs, W. O., Fritz, S. C., & Cook, E. R. (2010). Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. *Proceedings of the National Academy of Sciences of the United States of America*, 107(50), 6.
- Mead, D. J., & Gadgil, R. (1978). Fertiliser use in established radiata pine stands in New Zealand. *New Zealand Journal of Forestry Science*, 8(1), 105-134.

- Mead, D. J., & Gadgil, R. (1995). Using fertilisers to improve productivity of tree crops. In D. Hammond (Ed.), *Forestry Handbook* (3<sup>rd</sup> ed., pp. 240). Christchurch, New Zealand: NZ Institute of Forestry .
- Ministry of Agriculture and Forestry (MAF). (2013). *MAF domestic log grades*, from <http://www.maf.govt.nz/news-resources/statistics-forecasting/forestry/log-grade-specification.aspx>
- Ministry of Agriculture and Forestry (MAF). ( 2013). *Indicative New Zealand Radiata Pine Log Price*, from <http://www.maf.govt.nz/news-resources/statistics-forecasting/forestry/indicative-new-zealand-radiata-pine-log-prices.aspx>
- National Institute of Water and Atmospheric Research. (NIWA) (2010). Cliflo: The National Climate Database. Retrieved 18 June, 2012, from <http://cliflo.niwa.co.nz/>
- Newnham, R. M., & Lowe, D. J. (1999). Testing the synchronicity of pollen signals using tephrostratigraphy. *Global and Planetary Change*, 21, 113-128.
- Newsome, P. F. J., Wilde, R. H., & Willoughby, E. J. (Eds.). (2008) Land Resource information system spatial data layers. Palmerston North, New Zealand: Landcare Research
- Page, M. J., Trustrum, N.A., & De Rose, R.C. (1993). *A high-resolution record of storm-induced erosion from lake sediments, New Zealand*. Paper presented at the Sixth International Palaeolimnology Symposium, 19 - 21 April, Canberra.
- Page, M. J., Trustrum, N. A., & Dymond, J. R. (1994). Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand. *Geomorphology*, 9(3), 169-188.
- Palmer, D. J., Lowe, D. J., Payn, T. W., Höck, B. K., McLay, C. D. A., & Kimberley, M. O. (2005). Soil and foliar phosphorus as indicators of sustainability for *Pinus radiata* plantation forestry in New Zealand *Forest Ecology and Management*, 220(140-154).
- Pine Manufacturers. (2013). NZ Pine Users Guide: Log quality and conversion. Retrieved 2 March 2013, from <http://www.pine.net.nz/component/content/article/5-technical-specs/85-nz-pine-user-guide>
- Restrepo, C., Vitousek, P., & Neville, P. (2003). Landslides significantly alter land cover and the distribution of biomass: An example from the Ninole ridges of Hawai'i. *Plant Ecology*, 166(1), 131-143.
- Rosser, B. J., & Ross, C. W. (2011). Recovery of pasture production and soil properties on soil slip scars in erodible siltstone hill country, Wairarapa, New Zealand. *New Zealand Journal of Agricultural Research*, 54(1), 23-44.

- Smith, R. B., Commandeur, P. R., & Ryan, M. W. (1986). Soils, vegetation, and forest growth on landslides and surrounding logged and old-growth areas on the Queen Charlotte Islands. Victoria, B.C: Land Management Report No. 41. Canadian Forestry Service.
- Trustrum, N. A., Lambert, M. G., & Thomas, V. J. (1983). *The impact of soil erosion on hill country pasture production in New Zealand*. Paper presented at the Second International Conference on Soil Erosion and Conservation, Honolulu, Hawaii.
- Turner, J., & Lambert, M. J. (2011). Analysis of nutrient depletion in a radiata pine plantation. *Forest Ecology and Management*, 262(8), 1327-1336.
- West, G. G., Moore, J. R., Shula, R. G., Harrington, J. J., Snook, J., Gordon, J. A., & Riordan, M. P. (2012). *Forest management DSS development in New Zealand*. Paper presented at the 1st International Scientific Conference, Implementation of DSS into the forestry practice, Technical University, 10 May, Zvolen, Slovakia.
- Will, G. M. (1971). Nitrogen supply, apical dominance and branch growth in *Pinus radiata*. *Plant and Soil*, 34, (3) 515-517.
- Will, G. M. (1985). Nutrient deficiencies and fertiliser use in New Zealand exotic forests. *Forest Research Bulletin No 97*.
- Woollons, R. C., Skinner, M. F., Richardson, B., & Rijske, W. C. (2002). Utility of "A" horizon soil characteristics to separate pedological groupings, and their influence with climatic and topographic variables on *Pinus radiata* height growth. *New Zealand Journal of Forestry Science*, 32(2), 195-207.

## **Chapter Three: Estimating soil and nutrient losses in the Pakuratahi forest following erosion**

---

---

### 3.1 Introduction

#### *3.1.1 Background*

New Zealand loses approximately 400 million tonnes of soil annually through erosion and transport by rivers to the sea (MfE, 2013). Accelerated soil erosion is a significant problem in New Zealand hill country due to extensive deforestation firstly by early Polynesian settlers beginning in the late 13<sup>th</sup> century followed by large-scale land clearances by European settlers over the last ~200 years (McGlone, 1983; McGlone & Wilmshurst, 1999; Newnham & Lowe, 1999; McWethy *et al.*, 2010). Land use measures to mitigate the problem have included retiring formerly unproductive pasture land, planting of exotic deciduous species such as willow and poplar for erosion control, and planting permanent or plantation forestry. The hill country of Hawke's Bay on the east coast of the North Island in New Zealand has historically experienced high rates of accelerated erosion and currently has approximately 130,000 ha of exotic plantation forest (MPI, 2013).

#### *3.1.2 Site description*

Sites within a forest catchment located in the Hawke's Bay were studied to determine soil and nutrient loss following erosion (Chapter 2). Pakuratahi forest, managed by PanPac Ltd, is situated 21 km north of Napier at latitude 39° 20' 57" and longitude 176° 52' 30". The catchment is 774 ha and is classified as steep with flat to moderately rounded hills and ridges and narrow terraced valleys in the south. Elevation ranges from 18 m to 355 m above sea level. The Hawke's Bay climate is generally warm and dry but can experience highly variable extremes in rainfall and temperature. Rainfall is influenced by easterly and southerly winds ascending the high country in the west of the region (Thompson, 1987). An extreme rainfall event is described as such following rainfall exceeding 100 mm in 24 hours (NIWA, 2013).

The Pakuratahi catchment has experienced regular extreme rainfall events. Rainfall records from four stations neighbouring the Pakuratahi catchment recorded 80 days of rainfall over 100 mm between 1894 and 1993 (Fransen & Brownlie, 1995) Although rainfall-initiated erosion is dependent on terrain, vegetation cover, antecedent soil moisture, storm intensity

and duration, it is estimated that approximately 250 mm in two to three days is the minimum rainfall required to induce erosion in the Hawke's Bay hill country (Page *et al.*, 1993). Shallow mass movement erosion is the most common form of erosion in this region. Mass movement in the form of shallow landslides or soil slips generally result in the removal of much of the soil profile which includes organic matter, the top soil, and upper subsoil. Mass movement occurs in this landscape when pore-water pressures build up where the soil mantle makes contact with an impermeable boundary below. As the soil weakens and loses resistance, gravity transports the soil down the slope (NWSCA, 1985; Crozier, 1986). However, although this is a common occurrence in the east coast, very little research has been carried out in New Zealand as to effects of soil erosion on forestry.

### 3.1.3 Monitoring

In the USA, large scale erosion monitoring commenced in the 1950s to establish a database of actual and potential erosion risk for crop and agricultural land (Wischmeier & Smith, 1978). This led to the development of the Universal Soil Loss Equation (USLE) and subsequent Revised Universal Soil Loss Equation (RUSLE) which use rainfall, erodibility, slope length and steepness, and vegetation cover to estimate erosion. However, under forestry soil erosion has received less attention because of the time needed for long term monitoring projects and the difficulty in accessing remote terrain. To this end, various modifications have been applied to the standard RUSLE factors and their derivation to accommodate mountainous (Millward & Mersey, 1999) and forested environments (Prasannakumar *et al.*, 2012) using geographic information systems (GIS). In New Zealand, present and potential erosion types have been captured by the NZ Land Resource Inventory (NZLRI) (Newsome *et al.*, 2008). The NZLRI is a geospatial database stored within a geographic information system (GIS) and is based on five physical factors used for assessing Land Use Capability (LUC) (Lynn *et al.*, 2009) rock, soil, slope, erosion and vegetation (Newsome *et al.*, 2008). From these data, it has been estimated that 7.9 M ha (68.6%) of land in the North Island alone has the potential for mass movement erosion (Basher *et al.*, 2010).

Prior to afforestation, the Pakuratahi catchment experienced widespread erosion following extreme rainfall events. A series of aerial photographs of the area, taken from 1940 to 1994 were orthorectified and digitised, providing a geospatial output of maps and associated data (Table 3.1). The resulting map recorded events over 50 years, and coincided with land management changes and heavy rainfall (Fransen & Brownlie, 1995) (Fig. 3.1). These digital

layers provided the basis for the present field study of soil and nutrient loss in a northern sub-catchment of the Pakuratahi forest. Selected erosion scars under first rotation forestry were measured for size and sampled for soil analysis in order to estimate soil and nutrient loss from the area. The resulting data were extrapolated for the whole catchment to determine the scale of potential loss.

Table 3.1 Land use with associated extreme rainfall events (adapted from Fransen & Brownlie, 1995; Harrison *et al.*, in press)

<b>Year of storm</b>	<b>Rainfall mm/72 hr</b>	<b>Date of photographs</b>	<b>Photo scale</b>	<b>Reason for selection</b>
1938	800	Mar-43	1:17000	Erosion after April 1938 storm
1968	170	Nov-70	1:25000	Conditions prior to forest planting, erosion after 1968 storm
1980	190	Oct-81	1:25000	Forest cover in Pakuratahi catchment, erosion after 1980 storm
1988	490	Dec-88	1:25000	Erosion after Cyclone Bola, 1988
1989	220	Jan-94	1:27000	Conditions of site after 1989 event

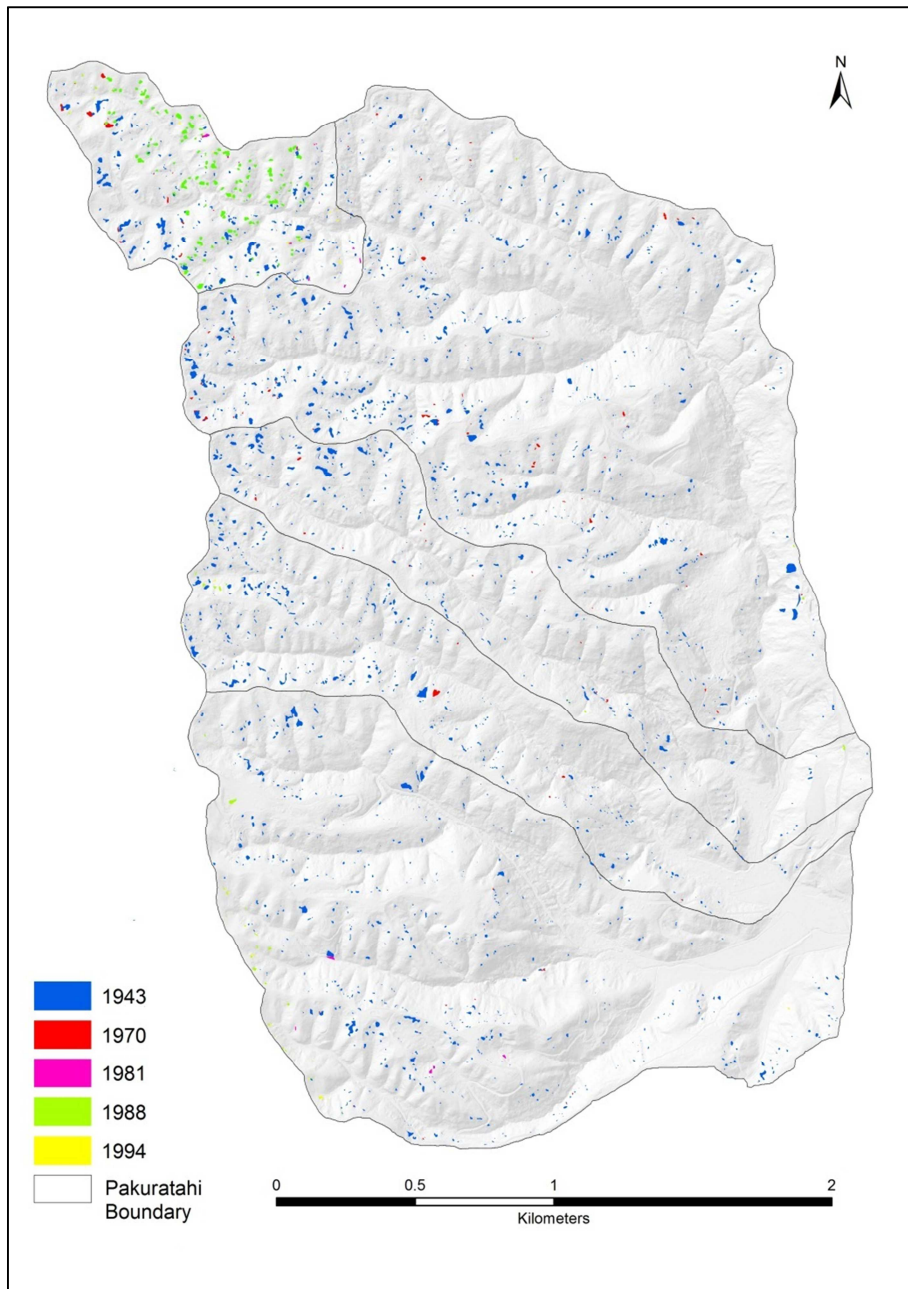


Figure 3.1 Mapped erosion over 50 years in Pakuratahi Forest. (adapted from digital layers created by Fransen & Brownlie, 1995)

#### *3.1.4 Models and classification*

Incorporating terrain attributes and LiDAR data recently captured for the Pakuratahi area, a detailed estimate of potential erosion following extreme rainfall events was determined using a non-linear regression model, (Harrison *et al.*, in press). Erosion data extracted from the NZLRI (Newsome *et al.*, 2008) and ESC (Bloomberg *et al.*, 2011) were overlaid by the Pakuratahi boundary to demonstrate some of the variation in interpretation of large scale models and nationwide classification. The Erosion Severity Classification (ESC) was developed by Bloomberg *et al.* (2011) to use in risk analysis for erosion, sedimentation and adverse environmental effects associated with forestry. Using NZLRI and LUC erosion severity data, the classification broadly categorises risk as high, moderate and low.

#### *3.1.5 Objectives*

The objectives of this study were to:

- i) estimate soil displacement from eroded areas in the northern catchment of Pakuratahi forest where plots were established to measure productivity; and
- ii) estimate potential soil nutrient losses from historical and future erosion events across the catchment.

## 3.2 Methods

### 3.2.1. Geospatial data

The GIS layers created from orthorectified aerial photographs which map the historical land use and erosion regime from 1940 to 1994 were used as a basis for plot selection in this project. Erosion scars of 0.02 ha and greater were identified in a desk top study using ESRI ArcMap 10.1 and then located in the field. The minimum scar size was designated at 0.02 ha to ensure there were enough trees to measure for the productivity study in chapter 2. The total recorded area of all mapped slips in Pakuratahi was calculated in a GIS by summing the areas of all slips.

### 3.2.2. Plot identification

Fifteen plots within erosion scars in the northern reaches of Pakuratahi forest were selected. The 15 plots located within erosion scars were paired with adjacent non-eroded land of similar aspect and slope to compare forest productivity (Figs. 3.2 & 3.3). One pair of plots was later dropped from the analysis due to an extreme washout of the eroded plot following heavy rainfall and channelling from an adjacent forest road.



Figure 3.2 Non-eroded terrain in Pakuratahi forest



Figure 3.3 Eroded terrain of similar aspect and slope forming pair with site in Fig 3.2

The intention was to identify known slip scars whose age could be estimated from stored digital surfaces and which were clearly defined in the field. Having installed the plots and recorded the position with both a Garmin GPSmap 60CSx and a Trimble ProXRT GPS, the sites were mapped onto a GIS. Only 6 eroded sites judged suitable for this study corresponded with the historically mapped sites of erosion. The 15 erosion scars were measured in the field. Length measurements were adjusted for slope. Depth was measured by suspending a field tape measure across the slip and measuring first the width, and then the depth at the centre of the measurement (Page *et al.*, 1999; M. Marden personal communication, June 22 2012). Depth and width measurements were taken at 5-m intervals along the length of each scar.

### 3.2.3 LiDAR

LiDAR image data were acquired on 24 August 2011, using New Zealand Aerial Mapping's Optech ALTM 3100EA LiDAR system. The data for Pakuratahi were collected by flying 900 m above lowest ground and using a scan angle of 10 degrees either side of nadir. The outgoing laser pulse rate (PRF) was set at 100 kHz and a mirror-scan frequency 67 Hz. The flight path was designed to generate a dataset with a minimum 4 points per square metre pulse density in open ground. The height accuracy of the classified ground points was checked by calculating height-difference statistics between a Triangulated Irregular Network (TIN) of the LiDAR ground points and the field-surveyed points. The standard deviation statistic for the data is +/-0.03 m. A 1 m DEM was generated from a TIN formed from the

ground-classified LiDAR points for the catchment (Harrison *et al.*, in press). Historical and study erosion sites were mapped onto the DEM.

### 3.2.4 Models and classification

A statistical model used to predict future landslides included the following variables: slope, soil type, lithology, elevation, aspect, vegetation cover, upstream flow length, flow accumulation, stream power index (SPI) and compound topographic index (CTI, steady state wetness index), and rainfall intensity. The Non-linear Regression model (NLRM) is based on the assumption that the catchment is under pasture (Harrison *et al.*, in press). Classification for potential erosion and erosion estimation using geospatial data associated with the NZLRI database and the ESC were applied to the Pakuratahi geospatial catchment using Arc Map 10.1 to gain an understanding of how each tool assessed either current or potential erosion.

## 3.3 Results

### 3.3.1 Field data

Each erosion scar chosen for analysis was measured for width, depth, length and slope to calculate the volume of potentially eroded soil (Table 3.2).

Table 3.2 Summary of erosion scar measurements ( $n = 14$ ) at study plots

	<b>Width (m)</b>	<b>Length (m)</b>	<b>Depth (m)</b>	<b>Slope (°)</b>	<b>Volume (m<sup>3</sup>)</b>
Range	9.7-15.6	12.4-24.2	0.5-2.3	20-33	59.8-713.1
Mean	12.4	17.7	1.2	26.2	277.5
C.I. 95%	1.2	1.7	0.3	2.3	113.0

Analysis values of soil samples taken from paired non-eroded plots were used to estimate nutrient loss from each slip. The rationale for using soil results from control plots was to simulate the historical soil profile that had been subsequently lost by erosion. Soils were sampled to a depth of 0.1 m and results averaged across all plots. For reporting purposes erosion losses are based on 0.1 m of displaced topsoil (Table 3.3).

Table 3.3 Estimated soil and soil nutrient losses from erosion events in Pakuratahi to a depth of 0.1 m (95% confidence interval in parentheses)

	<b>Per square metre (kg)</b>	<b>Per slip (n = 14) (kg)</b>	<b>Total volume of mapped slips throughout the catchment (t)</b>
Total carbon	2.26 (±0.42)	455.30 (±130.7)	270.93 (±50.8)
Total nitrogen	0.17 (±0.03)	33.95 (±9.7)	20.10 (±3.8)
Total phosphorus	0.02 (±0.004)	4.98 (±1.6)	2.95 (±0.53)
Total soil loss	2.63 (±0.928)	22.70 (±6.3)	2385.55 (±759.9)

Based on estimated soil volume from slip measurements and measured bulk density, around 415 tonnes (t) of soil has been displaced from the 14 measured slip scars. At a sampling depth of 0.1 m it was estimated that, on average, the eroded plots potentially lost 22 t of soil, 0.5 t of total C, 0.034 t of total N, and 0.005 t of total P. Extrapolating these data to encompass the 12 hectares of known slips from aerial photographs of Pakuratahi, there has potentially been a loss from this area of 2,385 t of soil, 271 t of carbon, 20 t of nitrogen, and 3 t of total phosphorus.

### 3.3.2 LiDAR and modelling

Hillshade was applied to the LiDAR generated DEMs to identify erosion scars. The research site locations and historical slips sites were mapped onto the DEM. However, the accuracy of alignment was tenuous leaving little room for definitive conclusions without further field measurements using GPS. In this instance, the ages of the eroded plots could not be established.

Using a nonlinear regression, Harrison et al. (in press) investigated a statistical approach to establish empirical relationships between rainfall intensity and landslides (Table 3.4). The “stable” category indicates areas that are the least susceptible to erosion risk with the “upper threshold” category being the most susceptible. (Figs: 3.5 & 3.6). Extreme rainfall events with a 0.8% and 1% exceedance probability were modelled based on storm events in 1938 (80-year event) and 1988 (100-year event). A 100-year extreme rainfall event has a return period of 1% which means there is a 1% chance this event could take place in any given year (Pearson & Henderson, 1998).

Table 3.4 Predicted slip and stability values for an 80- and a 100-year storm event in Pakuratahi catchment calculated using the regression modelling (adapted from Harrison et al., in press)

Stability Class	Stable	Moderately stable	Quasi-stable	Lower threshold	Upper threshold	Total
<b>80-year event</b>						
Area (km <sup>2</sup> )	1.27	1.24	0.84	3.50	0.89	7.74
% of Region	16.41	15.97	10.88	45.27	11.5	100
<b>100-year event</b>						
Area (km <sup>2</sup> )	2.19	0.81	0.34	1.51	2.89	7.74
% of Region	28.28	10.52	4.45	19.45	37.3	100

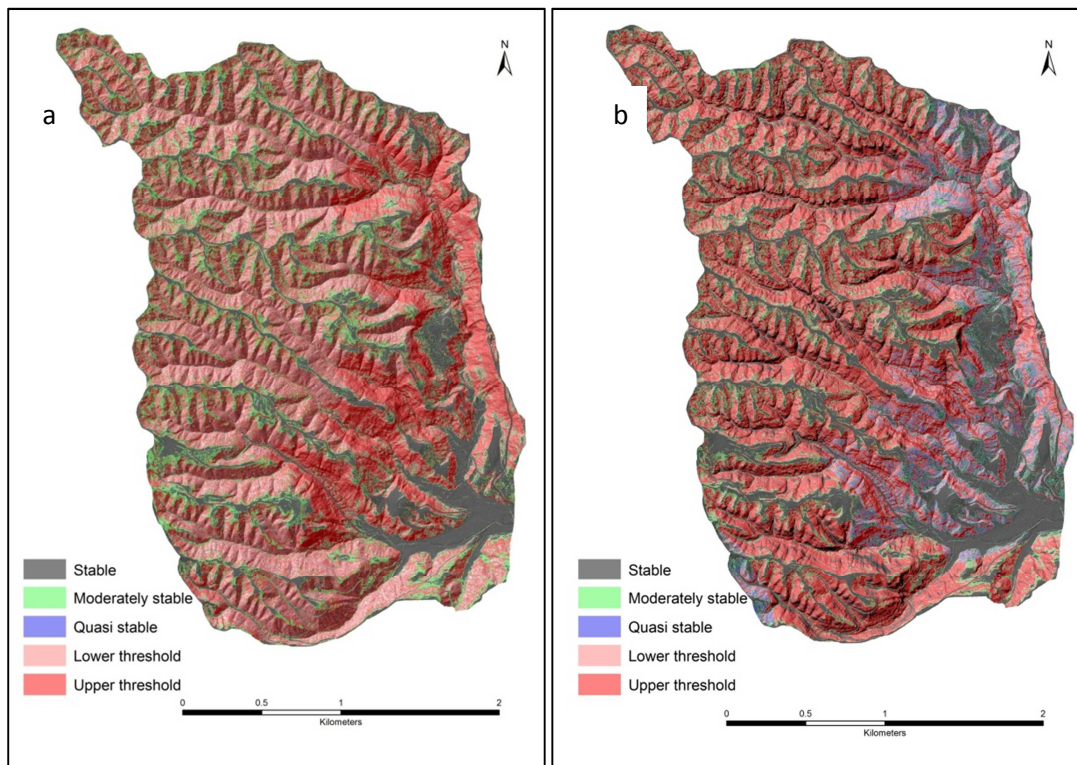


Figure 3.4 a) Non-linear regression model. Predicted erosion following: a) an 80-year high, rainfall event b) a 100-year high rainfall event

The potential soil and nutrient loss that could occur following these two modelled events, based on the estimated soil loss from measured slips at 0.1 m is outlined in Table 3.5.

Table 3.5 Estimated soil and nutrient loss using the NLRM model for an 80 year and 100 year extreme rainfall event

	<b>80 year event: 1 km<sup>2</sup> (tonnes)</b>	<b>100 year event: 3 km<sup>2</sup> (tonnes)</b>
Total carbon	2260	6780
Total nitrogen	170	510
Total phosphorus	20	60
Total soil loss	2630	7890

The model predicted that 1 km<sup>2</sup> of the total catchment area of 7.8 km<sup>2</sup> was at high risk of erosion from an 80-year event (Fig. 3.5), and nearly 3 km<sup>2</sup> was at risk from a 100-year event (Fig. 3.6). The accuracy of this model was tested against historical slip data in the Pakuratahi catchment and the relationship between actual and predicted data returned a correlation of R = 0.96 (Harrison *et al.*, in press). Extracting geospatial erosion data from NZLRI, the ESC, and the regression model in the Pakuratahi region revealed some variation in how each model predicted and classified risk (Table 3.6).

Table 3.6 Erosion susceptibility and prediction areas

<b>Models</b>	<b>Low</b>	<b>Area (ha)</b>	<b>Medium</b>	<b>Area (ha)</b>	<b>High</b>	<b>Area (ha)</b>	<b>Total area (ha)</b>
NZLRI	Negligible erosion	25	Slight to moderate	731	Nil	0	756
ESC	Low	26	Moderate	649	Very high	133	808
NLRM 80	Stable - moderately stable	251	Quasi stable - lower threshold	434	Upper threshold	89	774
NLRM 100	Stable - moderately stable	300	Quasi stable - lower threshold	185	Upper threshold	289	774

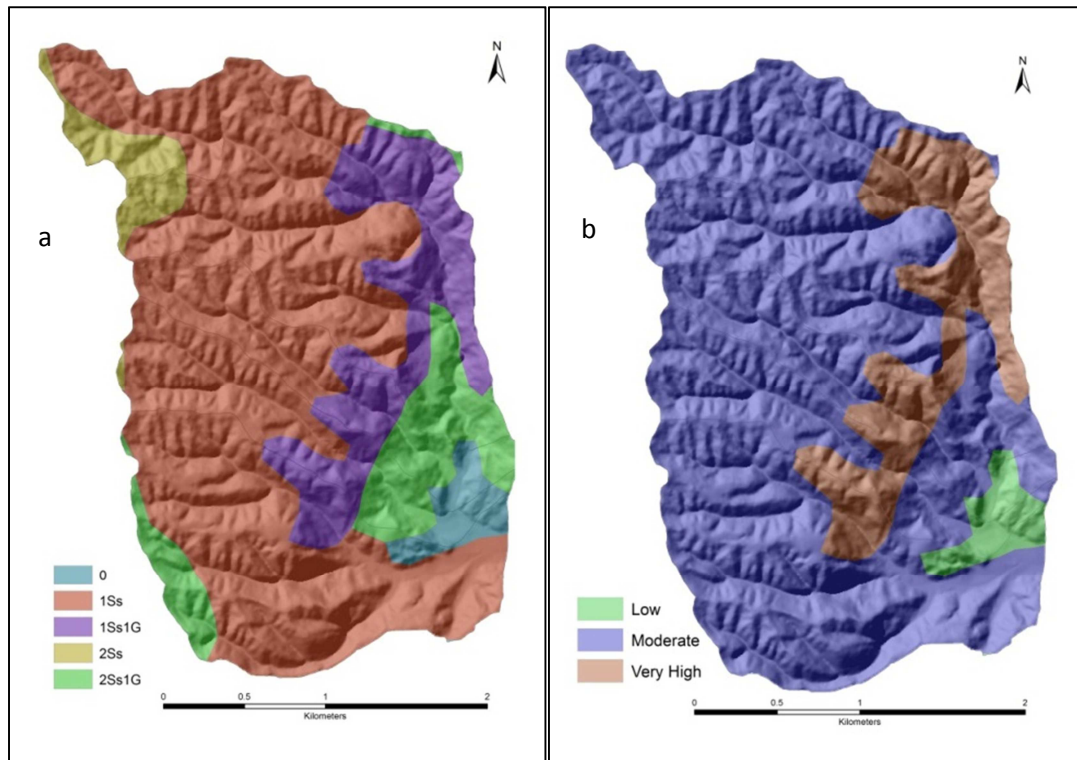


Figure 3.5 a) NZLRI erosion classification (Newsome *et al.*, 2008) Erosion severity: 0 = Negligible; 1 = slight; 2 = moderate. Erosion form name: Ss = soil slip, G = Gully  
 b) Erosion severity classification (Bloomberg *et al.*, 2011).

It is important to note that NZLRI erosion map indicates severity and form of current erosion, derived from aerial photographs and verification through field measurements. The ESC depicts the risks of erosion and potential downstream effects on the environment in association with plantation forestry using a conceptual model based on potential erosion classification in the NZLRI. The area described in the ESC map as being high risk for forestry and associated environmental effects is currently classified as experiencing slight soil and gully erosion.

## 3.4 Discussion

### 3.4.1 Erosion

Soil slip erosion does not necessarily result in an immediate loss of soil and nutrients from an area. The eroded soil and nutrients can be deposited at the base of the slip or ‘stored’ elsewhere in a catchment (such as colluvium or in the form of a terrace). However, there was little evidence of deposits at the base of the study plots in Pakuratahi with most slips being situated on steep sided gullies, leading directly down to streams. The lack of such deposits

led to the assumption that the eroded material was deposited in streams and washed downstream and following temporary storage as short-lived terraces. The results from soil analysis and field measurements suggest that potentially 415 tonnes of soil have eroded from the 14 measured erosion scars which cover an area of 2.4 hectares. It is uncertain over what period of time this has occurred because the age of each eroded site could not be determined. Only six eroded sites identified in the field corresponded with the historically mapped sites of erosion, leading to two potential explanations: i) the slips identified for the study had not been captured by earlier aerial photography ; or ii) less accuracy could be achieved by GPS survey on steep terrain and under 23 year old trees. Using the Trimble ProXRT GPS receiver, data were differentially corrected to an accuracy of 1–5 m. However, the majority of study slips appeared to be in the vicinity of the slips recorded in 1943 which would suggest continuing failure of earlier slips.

#### 3.4.2 Soil nutrients

An increase in soil nutrients over time due to litter accumulation is quite likely but because the age of the scars is unknown, it is not certain as to how much impact litter has made on eroded sites. Measured soil carbon has been found to decrease following afforestation of grasslands with *P. radiata* (Parfitt & Ross, 2011) but increases over time as pine litter accumulates, resulting in a higher soil total C (Davis & Condon, 2002; Paul *et al.*, 2002; Laganière *et al.*, 2010). Ultimately the most reliable measurement of change is to monitor the same site over time to give a more reliable indication of potential gains and losses following erosion events and subsequent afforestation. Research of this nature has not yet been carried out under forestry in New Zealand. The difference in forest productivity, with a reduction in biomass and tree volume recorded in eroded sites compared to non-eroded sites, has been noted (Smith *et al.*, 1986; Dean & Heron, 1998; Francescato *et al.*, 2001; Restrepo *et al.*, 2003) and is used as a measure of potential change.

There have been a number of studies involving pasture land in New Zealand which found pasture and topsoil recovery to be slow following erosion. Subsequently, measured topsoils contained fewer soil nutrients compared to soils in non-eroded areas, contributing to a reduction in pasture production. Rosser and Ross (2011) found that topsoil depths on eroded plots were around a third of topsoil depths measured in non-eroded sites. On average, pasture production on eroded hill country sites increased from 63 to 78% of that of non-eroded pasture over 25 years. Sparling *et al.* (2003) detected a recovery of 71-85% of topsoil

characteristics on eroded pasture for sheep farming compared to those of non-eroded sites after 59 years. Estimated recovery of degraded semi-arid hill country was found to be around 48 years (Parshotam & Hewitt, 1995). And on sites not limited by soil moisture conditions, pasture growth recovered to the levels of growth in non-eroded sites after 80 years in New Zealand hill country (DeRose *et al.*, 1995; in press).

### 3.4.3 Risk assessment

Without reliable time sequence monitoring of erosion under forestry, it is difficult to gauge historical losses. However, using LiDAR and GIS layers as a basis for models, the prediction of future erosion risk and soil loss is becoming more achievable. Harrison *et al.* (in press) used a non-linear empirical regression model to predict potential losses for at risk land in Pakuratahi under pasture. Although Pakuratahi is currently forested, the land is vulnerable to erosion after harvesting, and is susceptible to erosion during intense rainfall events in much the same way as land under pasture, during this time. Until the age of around 5 to 8 years, *P. radiata* forest plantations are susceptible to erosion following extreme rainfall events. Roots from the harvested crop tend to lose their tensile strength and new root mass from the next rotation takes time to increase and provide stability (Marden, 2004; O'Loughlin, 2005; Phillips *et al.*, 2013). Therefore, erosion prediction post-harvest is a useful tool for sustainable management.

## 3.5 Conclusions

The aim of this project was to estimate soil and nutrient losses from the 14 mapped erosion scars in the Pakuratahi forest and to gain an understanding of potential loss for the entire catchment. Using these data and a detailed empirical regression model, it was possible to calculate potential soil losses and predict future erosion following extreme rainfall events. Current prediction models and classification show some variation but are useful for providing a practical but broad guide for management. If the Pakuratahi forest is flown again for LiDAR at a later date, a comparison study could be completed to estimate soil loss by comparing current LiDAR data with that of the future. Gathering LiDAR data is expensive, however, and until this form of collection becomes more affordable, we will be relying on small catchment projects and prediction modelling. Future research could include developing

a nationwide method for monitoring and mapping ongoing erosion across New Zealand, and storing collected data in a central database that is easily updated.

### 3.6 References

- Basher, L. R., Barringer, J., Lynn, I. H., & Page, M. J. (2010). Accounting for the effects of mass-movement erosion on soil carbon stocks: defining and mapping land prone to mass movement erosion. Landcare Research
- Bloomberg, M., Davies, T., Visser, R., & Morgenroth, J. (2011). *Erosion Susceptibility Classification and Analysis of Erosion Risks for Plantation Forestry*. Ministry for the Environment from <http://www.mfe.govt.nz/laws/standards/forestry/erosion-susceptibility-classification.pdf>.
- Crosson, P. (1997). The on-farm economic costs of erosion. In R. Lal, W. H. Blum, C. Valentin & B. A. Stewart (Eds.), *Methods for assessment of soil degradation*. (pp. 495-511). Boca Raton: CRC Press.
- Crozier, M. J. (1986). *Landslides: causes, consequences and environment*. New Hampshire, USA: Croom Helm.
- Davis, M. R., & Condrón, L. M. (2002). Impact of afforestation on soil carbon in New Zealand: A review of paired site studies *Australian Journal of Soil Research*, 40(4), 675-690.
- Dean, M., & Heron, C. (1998). The effect of historical soil erosion on tree quality and volume: Report No. 58. Forest and Farm Plantation Management Cooperative.
- DeRose, R. C., Trustrum, N. A., Thomson, N. A., & Roberts, A. H. (1995). Effect of landslide erosion on Taranaki hill pasture production and composition. *New Zealand Journal of Agricultural Research*, 38(4), 457-471.
- Francescato, V., Scotton, M., Zarin, D. J., Innes, J. C., & Bryant, D. M. (2001). Fifty years of natural revegetation on a landslide in Franconia Notch, New Hampshire, U.S.A. *Canadian Journal of Botany*, 79(12), 1477-1485.
- Fransen, P., & Brownlie, R. (1995). Historical slip erosion in catchments under pasture and radiata pine forest, Hawke's Bay hill country. *NZ Forestry* (November), 29-33 .
- Harrison, D. R., Kimberley, M. O., Garrett, L. G., & Heaphy, M. J. (in press). *Testing two modelling approaches to landslide erosion in New Zealand* In press.
- Laganière, J., Angers, D. A., & Paré, D. (2010). Carbon accumulation in agricultural soils after afforestation. *Global Change Biology*, 16, 439-453.

- Lynn, I. H., Manderson, A. K., Page, M. J., Harmsworth, G. R., Eyles, G. O., Douglas, G. B., Mackay, A. D., & Newsome, P. J. F. (2009). *Land Use Capability Survey Handbook - a New Zealand classification of land, 3rd ed.* AgResearch Lt, Hamilton; Landcare Research New Zealand Ltd, Lincoln; Institute of Geological and Nuclear Sciences Ltd, Lower Hutt.
- McGlone, M. S. (1983). Polynesian deforestation of New Zealand: A preliminary synthesis. *Archaeology in Oceania*, 18(1), 11-25.
- McGlone, M. S., & Wilmshurst, J. M. (1999). Dating initial Maori environmental impact in New Zealand. *Quaternary International*, 59(1), 5-16.
- McWethy, D. B., Whitlock, C., Wilmhurst, J. M., McGlone, M. S., Fromont, M., Li, X., Dieffenbacher-Krall, A., Hobbs, W. O., Fritz, S. C., & Cook, E. R. (2010). Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. *Proceedings of the National Academy of Sciences of the United States of America*, 107(50), 6.
- Marden, M. (2004). Future-proofing erosion-prone hill country against soil degradation and loss during large storm events: Have past lessons been heeded? *New Zealand Journal of Forestry*, 49(3), 11-16.
- Millward, A. A., & Mersey, J. E. (1999). Adapting the RUSLE to model soil erosion potential in a mountainous tropical watershed. *CATENA*, 38(2), 109-129.
- Ministry for the Environment (MfE). (December 2007). Soil intactness of erosion-prone land. Retrieved 28 February 2013, from <http://www.mfe.govt.nz/environmental-reporting/land/erosion-risk/>
- Ministry for Primary Industries (MPI). New wood availability forecasts for the Hawke's Bay. Ministry of Primary Industries. Retrieved 2 March 2013, from <http://www.mpi.govt.nz/news-resources/news/new-wood-availability-forecasts-for-the-hawkes-bay>
- National Institute of Water and Atmospheric Research (NIWA). (2013). Extreme weather - heavy rainfall. 10 March 2013, from <http://www.niwa.co.nz/natural-hazards/extreme-weather-heavy-rainfall>
- National Water and Soil Conservation Authority (NWSCA). (1985). Resources for the future: New Zealand's National Water and Soil Conservation Survey. Wellington, New Zealand.

- Newnham, R. M., & Lowe, D. J. (1999). Testing the synchronicity of pollen signals using tephrostratigraphy. *Global and Planetary Change*, 21, 113-128.
- Newsome, P. F. J., Wilde, R. H., & Willoughby, E. J. (Eds.). (2008) Land Resource information system spatial data layers. Palmerston North, New Zealand: Landcare Research.
- O'Loughlin, C. (2005). The protective role of trees in soil conservation. *New Zealand Journal of Forestry*, 49(4), 9-15.
- Page, M. J., Reid, L. M., & Lynn, I. H. (1999). Sediment production from Cyclone Bola landslides, Waipaoa catchment. *Journal of Hydrology (NZ)*, 38(2), 289-308.
- Page, M. J., Trustrum, N. A., & De Rose, R. C. (1993). *A high-resolution record of storm-induced erosion from lake sediments, New Zealand*. Paper presented at the Sixth International Palaeolimnology Symposium, 19 - 21 April, Canberra.
- Parfitt, R. L., & Ross, D. J. (2011). Long-term effects of afforestation with *Pinus radiata* on soil carbon, nitrogen, and pH: a case study. *Soil Research*, 49, 494-503.
- Parshotam, A., & Hewitt, A. E. (1995). Application of the Rothamsted carbon turnover model to soils in degraded semi-arid land in New Zealand. *Environment International*, 21, 693-697.
- Paul, K. I., Polglase, P. J., Nyakuengama, J. G., & Khanna, P. K. (2002). Change in soil carbon following afforestation review *Forest Ecology and Management*, 168, 241-257.
- Pearson, C. P., & Henderson, R. D. (1998). Frequency distributions of annual maximum storm rainfalls in New Zealand. *Journal of Hydrology (NZ)*, 37(1), 19-33.
- Phillips, C., Marden, M., Lambie, S., Watson, A., Ross, C., & Fraser, S. (2013). Observations of below-ground characteristics of young redwood trees (*Sequoia sempervirens*) from two sites in New Zealand – implications for erosion control. *Plant and Soil*, 363(1-2), 33-48.
- Prasannakumar, V., Vijith, H., Abinod, S., & Geetha, N. (2012). Estimation of soil erosion risk within a small mountainous sub-watershed in Kerala, India, using Revised Universal Soil Loss Equation (RUSLE) and geo-information technology. *Geoscience Frontiers*, 3(2), 209-215.
- Restrepo, C., Vitousek, P., & Neville, P. (2003). Landslides significantly alter land cover and the distribution of biomass: An example from the Ninole ridges of Hawai'i. *Plant Ecology*, 166(1), 131-143.

- Rosser, B. J., & Ross, C. W. (2011). Recovery of pasture production and soil properties on soil slip scars in erodible siltstone hill country, Wairarapa, New Zealand. *New Zealand Journal of Agricultural Research*, 54(1), 23-44.
- Smith, R. B., Commandeur, P. R., & Ryan, M. W. (1986). Soils, vegetation, and forest growth on landslides and surrounding logged and old-growth areas on the Queen Charlotte Islands. Victoria, B.C: Land Management Report No. 41. Canadian Forestry Service.
- Sparling, G., Ross, D., Trustrum, N., Arnold, G., West, A., Speir, T., & Schipper, L. (2003). Recovery of topsoil characteristics after landslip erosion in dry hill country of New Zealand, and a test of the space-for-time hypothesis. *Soil Biology and Biochemistry*, 35(12), 1575-1586.
- Thompson, C. S. (1987). The climate and weather of Hawke's Bay. Series 115 (5) New Zealand Meteorological Service, Wellington.
- Wischmeier, W. H., & Smith, D. D. (1978). *Predicting rainfall erosion losses. A guide to conservation planning, agricultural handbook 537*, Washington, DC: US Department of Agriculture.

# **Chapter Four: Regional effects of erosion on forest productivity following extreme rainfall events Hawkes Bay**

## 4.1 Introduction

The climate in Hawke's Bay region, in east coast North Island, New Zealand, is largely influenced by the hilly terrain and airstreams crossing the country. Extremes of climate occur, ranging from drought to brief but intense cyclonic storms (Thompson, 1987). The relatively soft sedimentary rock underlying shallow tephric soils on steep slopes is susceptible to shallow landslides. Incidence of erosion may increase with slope (Schicker & Moon, 2012) particularly when the land is sparsely vegetated (Phillips *et al.*, 2013). The Hawke's Bay region was subjected to vast forest clearance, first by Polynesian settlers *ca* 1280 (McGlone & Wilmshurst, 1999; Wilmhurst *et al.*, 2008; McWethy *et al.*, 2010) followed by European immigrants from the mid-1800's onwards (McGlone, 1983). Following extreme rainfall events, severe erosion occurred on hill country pastureland in the Hawke's Bay. In a bid to prevent further erosion land owners were encouraged to plant trees particularly after Cyclone Bola in 1988 (MfE, 2013). But although the protective function of trees and forest has been well documented (Marden & Rowan, 1993; O'Loughlin, 2005) there has been very little research on the effects of soil erosion on forest productivity.

An understanding of the economic costs associated with decreased productivity on previously eroded land could assist with forecasting potential costs following future erosion events. In addition to establishing the costs of decreased productivity, benefits of afforestation such as ecosystem services need to be identified. An ecosystem service is defined as "the flow of value to human societies as a result of the state and quantity of natural capital" (TEEB, 2010) Ecosystem services are made up of three key areas: cultural services, regulating services, and provisioning services. The growing of timber is a provisioning service providing wood and fibre. Regulating services carried out by forests are slope stability and erosion control (Phillips *et al.*, 1989) provision of habitat (Pawson *et al.*, 2008; Bremer & Farley, 2010) flood control (Serengil *et al.*, 2011) carbon sequestration (Woollons & Manley, 2012) and the filtering of contaminants and nutrients near waterways (Dymond *et al.*, 2010). Planting forests on formerly eroded land will help to prevent further erosion but it comes at a cost to the landowner. In chapters 2 and 3, the loss in productivity for trees grown on formerly

measured erosion scars. Using existing geospatial data and prediction models, together with catchment-based field data, it is possible to gain an understanding of the potential effects of erosion on forests across Hawke's Bay and provide an insight into the scale of potential soil and nutrient loss following an extreme rainfall event. For this purpose, the well-documented extreme rainfall event caused by Cyclone Bola was used to analyse the effects of heavy rainfall induced soil erosion on forestry. The aims of this paper are to:

- i) Extract geospatial data in land use, slope, vegetation and topography layers from the NZLRI (Newsome *et al.*, 2008) to determine terrain within Hawke's Bay that aligns with the terrain surfaces in the Pakuratahi catchment;
- ii) Determine the costs and benefits to forestry with plantations planted on potentially erodible soils in Hawke's Bay

## 4.2 Methods

### 4.2.1 Study site description

A large tropical cyclone, Cyclone Bola hit New Zealand 7-9 March 1988, causing widespread flooding and landslides. Over a 3-day period, 753 mm of rain was recorded, with 320 mm and 329 mm occurring on successive days (Page *et al.*, 1994). Areas in which little soil conservation or flood control had been carried out experienced severe damage. Over 3,600 ha of farming and horticultural land were affected by flooding costing around \$90 million in damages (1988 values). Pasture and planted forests with trees aged 8 years and less were among the worst hit areas during the storm (Marden, 2004). In the time since Cyclone Bola caused widespread erosion, 1.3 million ha of forest have been planted across NZ. Of this land area, around 8% has been planted in Hawke's Bay (MPI, 2012). Hawke's Bay region is roughly 1.4 million ha and currently has had 112,000 ha of radiata pine planted since 1988.

Field data was collected in the Pakuratahi forest to supplement digital layers for analysis. Pakuratahi is a hilly to steep catchment 21 km north of Napier. Within the steepland catchment, 60% of the area contains slopes of over 21°. The three main soil orders (using the New Zealand Soil Classification; Hewitt (2010) in the catchment were identified as Pallic, Pumice and Recent Soils, with predominantly sandy loam topsoils (Eyles & Fahey, 2006; Newsome *et al.*, 2008). On the upper ridges and steep slopes, the Pumice Soils have formed *in situ* on the Taupo Tephra (erupted AD 232 ± 10 ) (Hogg *et al.*, 2012) and the Waimihia Tephra (erupted 3401 ± 108 cal. yr BP) (Lowe *et al.*, 2013). The underlying lithology consists of Tertiary and Cretaceous marine sedimentary rocks, mudstones and sandstones (Bland, 2007). The trees in the catchment at the time of this study were 23 years old.

### 4.2.2 Desk-top study

Erosion scars selected for field trials in the northern Pakuratahi catchment were identified with the aid of the digital surfaces mapping erosion in that area. Over 50 years of land-use change were recorded through a series of aerial photographs that were digitised and stored in a geographic information system (GIS) (Fransen & Brownlie, 1995) (Table 4.1).

Table 4.1 Aerial photographs of Pakuratahi used for mapping soil slips and land use with associated extreme rainfall events (adapted from Fransen and Brownlie, 1995; Harrison et al., in press)

<b>Year of storm</b>	<b>Rainfall mm/72 hr</b>	<b>Date of photographs</b>	<b>Photo scale</b>	<b>Reason for selection</b>
1938	800	Mar-43	1:17000	Erosion after April 1938 storm
1968	170	Nov-70	1:25000	Conditions prior to forest planting, erosion after 1968 storm
1980	190	Oct-81	1:25000	Forest cover in Pakuratahi catchment, erosion after 1980 storm
1988	490	Dec-88	1:25000	Erosion after Cyclone Bola, 1988
1989	220	Jan-94	1:27000	Conditions of site after 1989 event

A total of five surfaces were created, identifying landscape change from 1938 until 1996. The surfaces revealed an increased incidence in erosion following heavy rainfall when land was under pasture and decreased erosion when land was afforested. The digital surfaces and associated rainfall data gathered around the same time were collated to gain an understanding of the effect of heavy rainfall on the catchment over time.

#### 4.2.3 Field study

The selected eroded sites were measured for area and volume, sampled for soil analysis, and the trees growing on the scars were measured for height and diameter at breast height (dbh) to determine local forest productivity. The resulting data were collated to determine soil and nutrient loss across the catchment and to gain a measure of forest productivity on eroded sites (i.e. landslide scars) compared to non-eroded sites.

#### 4.2.4 GIS and economics

Growth simulation software, Atlas Forecaster (West *et al.*, 2012) was used to estimate the economic return from the trees measured in this trial. Using geospatial layers from the NZLRI, data from the Pakuratahi area were extracted and mapped using ESRI Arc GIS 10.1. The intention was to outline the predominant slope, soil order, and lithology in the catchment and to identify areas under plantation forest in Hawke's Bay with similar terrain characteristics to those in the Pakuratahi catchment. Productivity and soil loss variables estimated from the field study were then applied to this area to predict potential losses in the event of an extreme rainfall event. Current forestry statistics were accessed from the National Exotic Forest Description (2012).

### 4.3 Results

Slope, soil order, and rock type were extracted from the NZLRI database. Slopes of 21° or more (E to H) only, were included in the analysis. The codes and descriptions are given in Table 4.2.

Table 4.2 Slope class, NZLRI (adapted from Newsome et al., 2008)

<b>Item code</b>	<b>Class description</b>	<b>Class range</b>
E	Moderately steep	21–25°
F	Steep	25–35°
G	Very steep	35–42°
H	Precipitous	>42°

Two major soil orders found in Pakuratahi, Pallic and Pumice Soils, were identified throughout the Hawke’s Bay region. The major rock type was identified as sandstone with banded limestone which agrees with the definitions found in Haywick et al. (1991) and Bland et al. (2007) and Lee *et al.* (2010). Once extracted, the slope, soil, and rock-type data were spatially joined and overlaid by forestry data extracted from the Land cover database, version 3 (Landcare, 2013) to determine a target area of forestry that is currently growing on terrain similar to that of Pakuratahi (Fig. 4.1). The combined data produced the output given in Table 4.3.

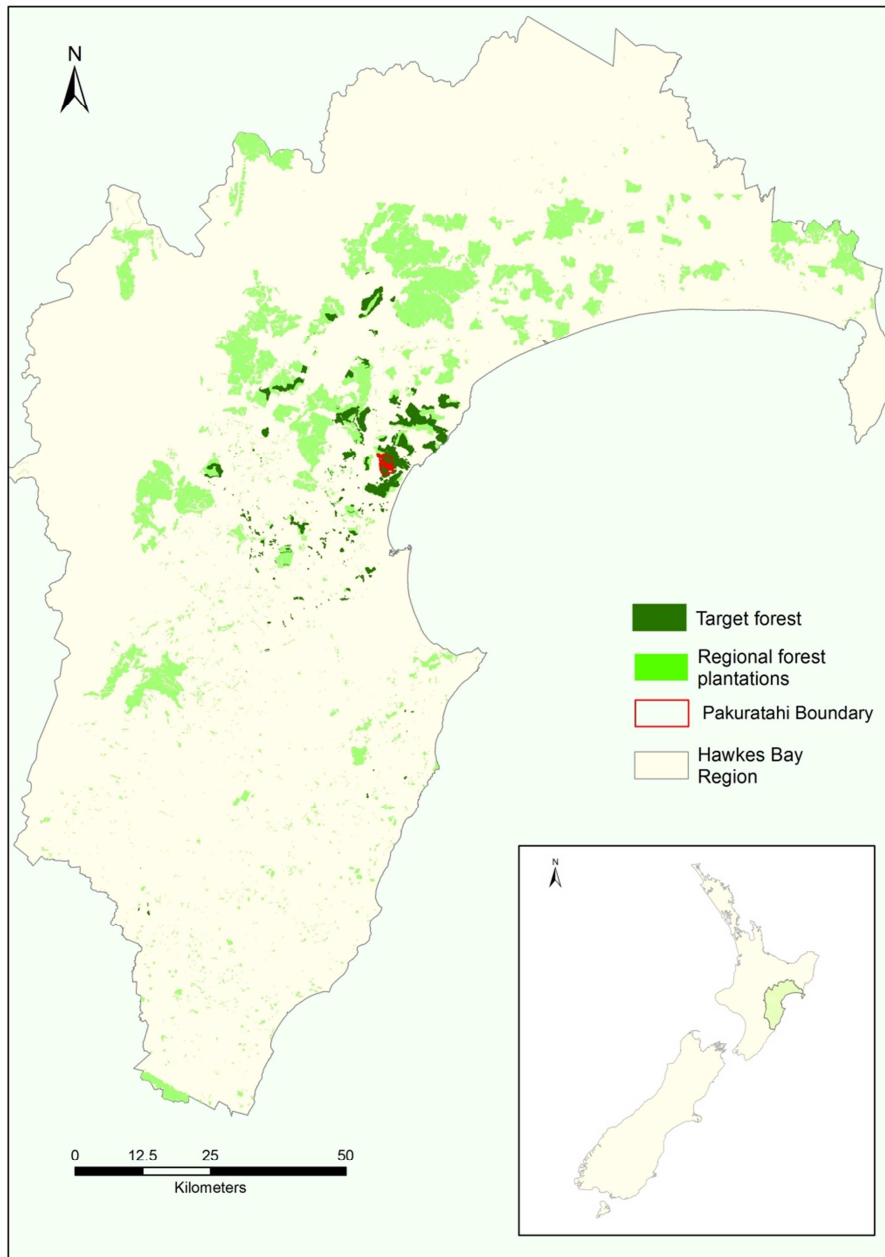


Figure 4.1 Hawke's Bay region outlining forest growing on Pallic and Pumice soils overlaying sandstones on slopes over 21° (Digital data accessed from NZLRI (Newsome et al., 2008 and LCDB3 (Landcare, 2013) databases. Mapped using Esri ArcMap 10.1

Table 4.3 Areas of terrain attributes in Hawke’s Bay region that correspond with those found in Pakuratahi

Area (km <sup>2</sup> )	Pumice Soils	Pallic Soils	Slopes > 21°	Lithology: sandstone and limestone	Target plantation forest	Combined (soil, slope, lithology, and forest)
Region	4478.8	2864.4	3926.3	348.4	1394.1	65.6
Pakuratahi	2.3	5.2	7.5	7.3	7.2	6.8

Analyses of terrains with similar lithologies, soils, and slopes to those of Pakuratahi returned an area of around 65 km<sup>2</sup> under plantation forest. Pakuratahi covered about 10% of this area.

#### 4.4 Discussion

An area 65 km<sup>2</sup> of plantation forest in the Hawkes was identified, with comparable soil and terrain attributes to the Pakuratahi catchment. In chapter 3, it was estimated that around 2.63 kg m<sup>-2</sup> of soil was lost from slopes following heavy rainfall-induced erosion. This is a conservative estimate because only 0.1 m of the soil profile was considered for analysis and the study covered a small area. Under forestry, potentially erodible land is more stable than under pasture (Fransen & Brownlie, 1995). Although slope failure is dependent on hydraulic conditions within the regolith and the response to rainfall events is both storm and site specific (Hawke & McConchie, 2011) mature *P. radiata* plantations have been shown to reduce mass movement erosion in high risk areas, decreasing sedimentation of streams and flood risk (Dymond *et al.*, 2012). Following harvesting however, the land is vulnerable until reforested. Old roots from the harvested crop begin to decay and lose their tensile strength. It can take up to 8 years before new root mass increases and provides slope stability (Marden & Rowan, 1993; Phillips *et al.*, 2013).

With the increasing unpredictability of intense rainfall events, potentially as a result of climate change, forest managers could benefit from being able to estimate the costs of land degradation should areas of steepland forestry be subjected to accelerated erosion between forest rotations. If we apply the estimate of 2.63 kg m<sup>-2</sup> to the area of 65 km<sup>2</sup> of land that was identified as having similar terrain attributes to Pakuratahi, up to 169,000 tonnes of soil could potentially be lost following an extreme rainfall event in Hawke’s Bay. Based on soil chemical analyses from the Pakuratahi catchment (Chapter 2), the associated nutrient loss was calculated as 146900 t of carbon, 11050 t of nitrogen and 1300 t of phosphorus.

A considerable body of research attests to the benefits of afforestation of hilly or unstable land (Hawley & Dymond, 1988; Hicks, 1991; Basher *et al.*, 2010; Dymond *et al.*, 2010; Rosser & Ross, 2011). Following Cyclone Bola there has been an increased move to afforest potentially unstable land with permanent and plantation forest particularly in the worst hit regions such as the East Coast of the North Island. There is, however, a cost to the land owner/manager for growing trees on formerly eroded land due to smaller logs and the requirements of remedial action such as fertilisation. The study carried out in the northern catchment of Pakuratahi (Chapter two) revealed that trees grown on eroded sites yielded 16% less volume for high quality logs than trees in non-eroded sites. A reduction in volume of this magnitude equates to around \$4,000 per hectare in decreased revenue (Chapter 2). The reduction in total recoverable volume for all grades of logs was estimated at around \$7,500 per hectare on eroded sites (Chapter 2).

The costs associated with loss in revenue because of decreased productivity are thus considerable. The value of the services provided by afforestation of hill country terrain is also significant, providing potential savings through topsoil preservation, preventing sedimentation of waterways and subsequent flooding in low-lying areas. In a study on the costs of avoided erosion, Barry *et al.* (2012) concluded that regions in New Zealand with high erosion rates would provide high levels of net public benefit following afforestation. Where the net private benefits were moderately negative, policy makers could adopt positive incentives through funding or technology improvement. Dymond *et al.* (2012) estimated the cost of avoided erosion to be worth NZ \$1 per tonne. In this study we have estimated that approximately 65 km<sup>2</sup> of land in the Hawkes Bay is at risk of erosion similar to that in the Pakuratahi Catchment following an extreme rainfall event and a potential soil loss of 169000 tonnes if not forested. If forest owners are losing \$7500 in total recoverable value per hectare on eroded soil in the Pakuratahi, the value of avoided erosion for post Cyclone Bola plantations in Hawke's Bay with similar terrain attributes, is estimated around \$288 per tonne of soil.

Production forestry's contribution to erosion prevention through existing plantations is not recognised financially across New Zealand. There are however, two major funded forestry incentive schemes in NZ: the East Coast Forestry Project (ECFP) and the Permanent Forest Sink Initiative (PFSI) (MPI, 2013) that the industry can access. The ECFP was established in a bid to control current and prevent future soil erosion in the Gisborne district. The 2010 grant rates for forestry are graded according to the distance from Gisborne port (Table 4.4).

Table 4.4 East Coast Forestry Project Grant rates (MPI, 2010)

<b>Treatment</b>	<b>Distance from Gisborne Port (km)</b>	<b>Grant rates</b>
Forestry	0–80	\$1 476/ha
Forestry	81–150	\$2 014/ha
Forestry	151– 215	\$2 280/ha

Target land classified under the Land use classifications (Lynn *et al.*, 2009) includes classes 7e and Classes 8e which are generally only suitable for forestry or conservation land. The LUC subclass ‘e’ is a limitation: erodibility – “where susceptibility to erosion is the dominant limitation” (Lynn *et al.*, 2009, pg. 9). Another incentive to establish permanent forests on land previously unforested since 31 December 1989 is given by the PFSI, which aims to facilitate carbon sequestration in permanent forest sinks. Landowners are able to apply for carbon credits under the NZ Emissions trading scheme (ETS) but there are financial penalties for losses in stored carbon (e.g. through clear fell harvesting or damage through a natural event) and fees to join the scheme. In addition there is a potential risk from future carbon price uncertainty (Manley, 2013).

Incentive schemes like ECFP and PFSI, while useful, do not address the service that forestry is currently providing through establishing plantations on potentially erodible soils. In order to be truly effective for erosion control, a growing awareness of and research into, the ecosystem services that forestry provides will be needed in order to lobby for positive policy changes towards financial recognition of ecosystem services. Dominati *et al.* (2010) examined soil forming processes and soil properties to develop a framework that classified and quantified soils natural capital and ecosystem services. Using this framework they established that the regulating services of soils under a Waikato dairy farm had greater value from regulating than provisioning services (Dominati *et al.*, 2011). While forestry’s provisioning services of producing timber are recognised, the regulating services of avoided erosion and flood control are not. A similar framework developed for forestry would firstly qualify the ecosystem services provided by afforestation and secondly make provision for financial recognition for services with far reaching benefits. In time, financial recognition of the ecosystem services provided by forestry may encourage land managers to explore alternatives management methods. These could include planting regimes such as continuous cover where ‘the management of forests by following natural processes so that the forest canopy is always maintained at one or more levels and the forest will largely self-regenerate’

(Barton, 2008). Or less intensive harvesting and mixed species planting to prevent erosion mid rotation.

## 4.5 Conclusions

Afforestation of steepland and hill country in the east coast of the North Island has contributed to a decrease in soil erosion and an increase in flood control following extreme rainfall events. Around 65 km<sup>2</sup> of potentially erodible land in the Hawkes Bay region was identified as having similar terrain attributes as Pakuratahi, with shallow soils over sandstone, steep slopes and supporting plantation forestry. Because the Pakuratahi catchment is the only area that has forest productivity related research carried out, only areas in the Hawkes Bay that had the same terrain attributes under plantation forest were included in the analysis. There will be many other locations within the region that have forest plantation on potentially erodible soils. Trees planted on eroded soils in the Pakuratahi resulted in a 16% lower return in volume compared to those planted on non-eroded sites. The costs to the landowner were estimated to be around \$7500 per ha in lost productivity. These costs are borne by the landowner but could be offset if the ecosystem services of avoided erosion were recognised financially. Future research is needed to develop a framework that classifies and quantifies the regulating services provided by forestry so that the value of afforestation of highly erodible land is fully recognised.

## 4.6 References

- Adams, J. (1980). Contemporary Uplift and Erosion of the Southern Alps, New Zealand. *Geological Society of America Bulletin*, 91(2), 115.
- Ballard, R. (1970). The phosphate status of the soils of Riverhead Forcst in relation to growth of radiata pine. *New Zealand Journal of Forestry*, 15(1).
- Barry, L. E., Yao, R., Paragahawewa, U., & Harrison, D. R. (2012). *Where and how can policy encourage afforestation to avoid soil erosion*. Paper presented at the New Zealand Agricultural and Resource Economics Society (Inc) 30 & 31 August, Tahuna Conference Centre, Nelson, New Zealand.
- Barton, I. (2008). *Continuous cover forestry: A handbook for the management of New Zealand forests*. . Pukekohe, New Zealand: Tane's Tree Trust.
- Basher, L. R., Barringer, J., Lynn, I. H., & Page, M. J. (2010). Accounting for the effects of mass-movement erosion on soil carbon stocks: defining and mapping land prone to mass movement erosion. Landcare Research
- Bland, K. J., Kamp, P. J. J., & Nelson, C. S. (2007). *Systematic Lithostratigraphy of the Neogene succession exposed in central parts of Hawke's Bay Basin, eastern North Island, New Zealand*. Ministry of Economic Development New Zealand Unpublished Petroleum Report PR3724.
- Blaschke, P. M., Trustrum, N. A., & Hicks, D. L. (2000). Impacts of mass movement erosion on land productivity: A review. *Progress in Physical Geography*, 24(1), 21-52.
- Bloomberg, M., Davies, T., Visser, R., & Morgenroth, J. (2011). *Erosion Susceptibility Classification and Analysis of Erosion Risks for Plantation Forestry*. Ministry for the Environment from <http://www.mfe.govt.nz/laws/standards/forestry/erosion-susceptibility-classification.pdf>.
- Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic and available forms of phosphorus in soils. *Soil Science*, 59, 39-45.
- Bremer, L. L., & Farley, K. A. (2010). Does plantation forestry restore biodiversity or create green deserts? A synthesis of the effects of land-use transitions on plant species richness. *Biodiversity and Conservation*, 19(14), 3893-3915.
- Crosson, P. (1997). The on-farm economic costs of erosion. In R. Lal, W. H. Blum, C. Valentin & B. A. Stewart (Eds.), *Methods for assessment of soil degradation*. (pp. 495-511). Boca Raton: CRC Press.

- Crozier, M. J. (1986). *Landslides: causes, consequences and environment*. New Hampshire, USA: Croom Helm.
- Davis, M. R., & Condron, L. M. (2002). Impact of afforestation on soil carbon in New Zealand: A review of paired site studies *Australian Journal of Soil Research*, 40(4), 675-690.
- Davis, M. R., Grace, L. J., & Horrell, R. F. (1996). Conifer establishment in South Island high country: Influence of mycorrhizal inoculation, competition removal, fertiliser application, and animal exclusion during seedling establishment. *New Zealand Journal of Forestry Science*, 26(3), 380-394.
- Davis, M. R., & Lang, M. H. (1991). Increased nutrient availability in topsoils under conifers in the south island high country. *NZ Journal of Forestry Sciences*, 21, 165-179.
- Dean, M., & Heron, C. (1998). The effect of historical soil erosion on tree quality and volume: Report No. 58. Forest and Farm Plantation Management Cooperative.
- DeRose, R. C., Trustrum, N. A., Thomson, N. A., & Roberts, A. H. C. (1995). Effect of landslide erosion on Taranaki hill pasture production and composition *New Zealand Journal of Agricultural Research*, 38, 457-471.
- Dominati, E., Mackay, A., & Patterson, M. (2010). *Modelling the provision of ecosystem services from soil natural capital*. Paper presented at the World Congress of Soil Science: Soil solutions for a changing world, Brisbane, Australia.
- Dominati, E., Mackay, A. D., Green, S., & Patterson, M. (2011). The value of soil services for nutrient management. In: Adding to the knowledge base for the nutrient manager. In L. D. Currie & C. L. Christensen (Eds.), *24th Annual Fertiliser and Lime Research Centre Workshop*, Occasional report No. 24, 1-8, Palmerston North, New Zealand: Massey University.
- Dyck, W. J., & Skinner, M. F. (1990). *Potential for Productivity Decline in New Zealand Radiata Pine Forests*. Paper presented at the Sustained Productivity of Forest Soils Conference, University of British Columbia, Vancouver, British Columbia.
- Dymond, J. R., Ausseil, A. G. E., Ekanayake, J. C., & Kirschbaum, M. U. F. (2012). Tradeoffs between soil, water, and carbon - A national scale analysis from New Zealand. *Journal of Environmental Management*, 95(1), 124-131.
- Dymond, J. R., Betts, H. D., & Schierlitz, C. S. (2010). An erosion model for evaluating regional land-use scenarios. *Environmental Modelling & Software*, 25(3), 289-298.
- Ellis, J. C., & Hayes, J. D. (1997). Field guide for sample plots in New Zealand forests. *Forest Research Institute Bulletin No 186*.

- Eyles, G. O. (1983). The Distribution and Severity of Present Soil Erosion in New Zealand. *New Zealand Geographer*, 39(1), 12-28.
- Eyles, G.O., Fahey, B.D. (2006). Introduction. In: G.O. Eyles, B.D. Fahey (Eds.), The Pakuratahi Land Use Study. A 12 year paired catchment study of the Environmental effects of Pinus radiata Forestry, Hawke's Bay Regional Council.
- Federer, C. A., Turcotte, D. E., & Smith, C. T. (1993). The organic fraction - bulk density relationship and the expression of nutrient content in forest soils. *Canadian Journal of Forest Research*, 23.
- Francescato, V., Scotton, M., Zarin, D. J., Innes, J. C., & Bryant, D. M. (2001). Fifty years of natural revegetation on a landslide in Franconia Notch, New Hampshire, U.S.A. *Canadian Journal of Botany*, 79(12), 1477-1485.
- Fransen, P., & Brownlie, R. (1995). Historical slip erosion in catchments under pasture and radiata pine forest, Hawke's Bay hill country. *NZ Forestry*, (November), 29-33.
- Froggart, P. C., & Lowe, D. J. (1990). A review of late Quaternary silicic and some other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution, volume, and age. *New Zealand Journal of Geology and Geophysics*, 33(1), 89-109.
- Gibbs, H. S., & Raeside, J. D. (1945). Soil erosion in the High Country of the South Island: New Zealand Department of Scientific and Industrial Research Bulletin 92.
- Glade, T. (1998). Establishing the frequency and magnitude of landslide-triggering rainstorm events in New Zealand. *Environmental Geology*, 35(2-3), 160-174.
- Goulding, C. J. (2005). Measurement of trees. In M. Colley (Ed.), *NZIF Forestry Handbook* (4th ed ed.). Christchurch, New Zealand: New Zealand Institute of Forestry.
- Grange, L. I., & Gibbs, H. S. (1947). Soil erosion in New Zealand. Part 1. Southern half North Island: New Zealand Soil Bureau Bulletin 1.
- Grigal, D. F., & Vance, E. D. (2000). Influence of soil organic matter on forest productivity. *New Zealand Journal of Forstry Science*, 30(1/2).
- Harrison, D. R., Kimberley, M. O., Garrett, L. G., & Heaphy, M. J. (in press). *Testing two modelling approaches to landslide erosion in New Zealand* In press.
- Hawke, R., & McConchie, J. (2011). In situ measurement of soil moisture and pore-water pressures in an 'incipient' landslide: Lake Tutira, New Zealand. *Journal of Environmental Management*, 92(2), 266-274.
- Hawley, J. G., & Dymond, J. R. (1988). How much do trees reduce landsliding? *Journal of Water and Soil Conservation*, 43, 495-498.

- Haywick, D. W., Lowe, D. A., Beu, A. G., Henderson, R. A., & Carter, R. M. (1991). Pliocene-Pleistocene (Nukumaruan) lithostratigraphy of the Tangoio block, and origin of sedimentary cyclicity, central Hawke's Bay, New Zealand. *New Zealand Journal of Geology & Geophysics*, 34(2), 213-225.
- Hewitt, A. E. (2010). *New Zealand Soil Classification* (2nd ed.). Lincoln, New Zealand: Manaaki Whenua Press.
- Hicks, D. L. (1991). Erosion under pasture, pine plantations, scrub and indigenous forest. *New Zealand Forestry*, 26, 21-22.
- Hogg, A. G., Lowe, D. J., Palmer, J. G., Boswijk, G., & Bronk Ramsey, C. J. (2012). Revised calendar date for the Taupo eruption derived by 14C wiggle-matching using a New Zealand kauri 14C calibration data set. *The Holocene*, 22, 439-449.
- Kimberley, M., West, G. G., Dean, M. G., & Knowles, R. L. (2005). The 300 index - a volume productivity index for radiata pine. *New Zealand Journal of Forestry*, 50, 13-18.
- Laganière, J., Angers, D. A., & Paré, D. (2010). Carbon accumulation in agricultural soils after afforestation. *Global Change Biology*, 16, 439-453.
- Lal, R. (1987). Effects of soil conservation on crop productivity. *Critical Review of Plant Science* 5, 303-367.
- Lal, R. (2001). Soil degradation by erosion. *Land Degradation & Development*, 12(6), 519-539.
- Lambert, M. G., Trustrum, N. A., & Costall, D. A. (1984). Effects of soil slip erosion on seasonally dry Wairarapa hill pastures. *New Zealand Journal of Agricultural Research*, 27(1), 57-64.
- Landcare Research . (2013). Landcover database 3, National Land Resource Centre. from <http://www.nlrc.org.nz/home>
- Lee, J.M.; Townsend, D.; Bland, K.; Kamp, P.J.J. (compilers) 2011: Geology of the Hawke's Bay area: scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences Limited. Institute of Geological & Nuclear Sciences 1:250,000 geological map 8.1, 93 p. + 1 folded map.
- Lowe, D. J., Blaauw, M., Hogg, A. G., & Newnham, R. M. (2013). Ages of 24 widespread tephra erupted since 30,000 years ago in New Zealand, with re-evaluation of the timing and palaeoclimatic implications of the late-glacial cool episode recorded at Kaipo bog. *Quaternary Science Reviews* from <http://dx.doi.org/10.1016/j.quascirev.2012.11.022>

- Lynn, I. H., Manderson, A. K., Page, M. J., Harmsworth, G. R., Eyles, G. O., Douglas, G. B., Mackay, A. D., & Newsome, P. J. F. (2009). *Land Use Capability Survey Handbook - a New Zealand classification of land* (3rd ed.) AgResearch Lt, Hamilton; Landcare Research New Zealand Ltd, Lincoln; Institute of Geological and Nuclear Sciences Ltd, Lower Hutt.
- Manley, B. (2013). How does real option value compare with Faustmann value in the context of the New Zealand Emissions Trading Scheme? *Forest Policy and Economics*(0). doi: <http://dx.doi.org/10.1016/j.forpol.2013.02.001>
- Marden, M. (2004). Future-proofing erosion-prone hill country against soil degradation and loss during large storm events: Have past lessons been heeded? *New Zealand Journal of Forestry*, 49(3), 11-16.
- Marden, M., & Rowan, D. (1993). Protective value of vegetation on tertiary terrain before and during Cyclone Bola, East Coast, North Island, New Zealand. *New Zealand Journal of Forestry Science*, 23(3), 255-263.
- McGlone, M. S. (1983). Polynesian deforestation of New Zealand: A preliminary synthesis. *Archaeology in Oceania*, 18(1), 11-25.
- McGlone, M. S., & Wilmschurst, J. M. (1999). Dating initial Maori environmental impact in New Zealand. *Quaternary International*, 59(1), 5-16.
- McLaren, J. P. (1993). *Radiata Pine Grower's Manual 184*, Rotorua: New Zealand Forest Research Institute Ltd.
- McLaren, R. G., & Cameron, K. C. (2005). *Soil Science: Sustainable production and environmental protection*. Melbourne, Australia: Oxford University Press.
- McSaveney, E. 'Floods - Southland floods and Cyclone Bola', Te Ara - the Encyclopedia of New Zealand, updated 13 July 2012 from <http://www.TeAra.govt.nz/en/floods/page-4>
- McWethy, D. B., Whitlock, C., Wilmschurst, J. M., McGlone, M. S., Fromont, M., Li, X., Dieffenbacher-Krall, A., Hobbs, W. O., Fritz, S. C., & Cook, E. R. (2010). Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. *Proceedings of the National Academy of Sciences of the United States of America*, 107(50), 6.
- Mead, D. J., & Gadgil, R. (1978). Fertiliser use in established radiata pine stands in New Zealand. *New Zealand Journal of Forestry Science*, 8(1), 105-134.
- Mead, D. J., & Gadgil, R. (1995). Using fertilisers to improve productivity of tree crops. In D. Hammond (Ed.), *Forestry Handbook* (3<sup>rd</sup> ed.) Christchurch, New Zealand: NZ Institute of Forestry.

- Millward, A. A., & Mersey, J. E. (1999). Adapting the RUSLE to model soil erosion potential in a mountainous tropical watershed. *CATENA*, 38(2), 109-129. doi: [http://dx.doi.org/10.1016/S0341-8162\(99\)00067-3](http://dx.doi.org/10.1016/S0341-8162(99)00067-3)
- Ministry of Agriculture and Forestry (MAF) (2013). *MAF domestic log grades*, from <http://www.maf.govt.nz/news-resources/statistics-forecasting/forestry/log-grade-specification.aspx>
- Ministry of Agriculture and Forestry (MAF) (2013). *Indicative New Zealand Radiata Pine Log Price*, from <http://www.maf.govt.nz/news-resources/statistics-forecasting/fomafrestry/indicative-new-zealand-radiata-pine-log-prices.aspx>
- Ministry for the Environment. (MfE) (2013, December 2007). Soil intactness of erosion-prone land. Retrieved 28 February 2013, from <http://www.mfe.govt.nz/environmental-reporting/land/erosion-risk/>
- Ministry for Primary Industries (MPI). (2013). New wood availability forecasts for the Hawke's Bay. Retrieved 2 March 2013, from <http://www.mpi.govt.nz/news-resources/news/new-wood-availability-forecasts-for-the-hawkes-bay>
- Ministry for Primary Industries (MPI). (2012). East Coast Forestry Project. Retrieved 6 March 2013, from <http://www.mpi.govt.nz/forestry/funding-programmes/east-coast-forestry-project>
- Ministry for Primary Industries (MPI). (2012). *National Exotic Forest Description*. Wellington, from <http://www.mpi.govt.nz/news-resources/publications.aspx?title=National%20Exotic%20Forest%20Description>
- National Institute of Water and Atmospheric Research (NIWA). (2013). Extreme weather - heavy rainfall. from <http://www.niwa.co.nz/natural-hazards/extreme-weather-heavy-rainfall>
- National Institute of Water and Atmospheric Research (NIWA). (2010). Cliflo: The National Climate Database. Retrieved 18 June, 2012, from <http://cliflo.niwa.co.nz/>
- National Water and Soil Conservation Authority (NWSCA). (1985). Resources for the future: New Zealand's National Water and Soil Conservation Survey. Wellington, New Zealand.
- Newnham, R. M., & Lowe, D. J. (1999). Testing the synchronicity of pollen signals using tephrostratigraphy. *Global and Planetary Change*, 21, 113-128.
- Newsome, P. F. J., Wilde, R. H., & Willoughby, E. J. (Eds.). (2008) Land Resource information system spatial data layers. Palmerston North, New Zealand: Landcare Research.

- O'Loughlin, C. (2005). The protective role of trees in soil conservation. *New Zealand Journal of Forestry*, 49(4), 9-15.
- Page, M. J., Reid, L. M., & Lynn, I. H. (1999). Sediment production from Cyclone Bola landslides, Waipaoa catchment. *Journal of Hydrology (NZ)*, 38(2), 289-308.
- Page, M. J., Trustrum, N. A., & De Rose, R. C. (1993). *A high-resolution record of storm-induced erosion from lake sediments, New Zealand*. Paper presented at the Sixth International Palaeolimnology Symposium, 19 - 21 April, Canberra.
- Page, M. J., Trustrum, N.A., DeRose, R.C. (1994). A high resolution record of storm induced erosion from lake sediments, New Zealand. *Journal of Paleolimnology*, 11, 333-348.
- Page, M. J., Trustrum, N. A., & Dymond, J. R. (1994). Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand. *Geomorphology*, 9(3), 169-188.
- Palmer, D. J., Lowe, D. J., Payn, T. W., Höck, B. K., McLay, C. D. A., & Kimberley, M. O. (2005). Soil and foliar phosphorus as indicators of sustainability for *Pinus radiata* plantation forestry in New Zealand *Forest Ecology and Management*, 220(140-154).
- Palmer, D. J., Watt, M. S., Kimberley, M. O., Hock, B. K., Payn, T. W., & Lowe, D. J. (2010). Mapping and explaining the productivity of *Pinus radiata* in New Zealand. *New Zealand Journal of Forestry*, 55(1), 15-21.
- Parfitt, R. L., & Ross, D. J. (2011). Long-term effects of afforestation with *Pinus radiata* on soil carbon, nitrogen, and pH: a case study. *Soil Research*, 49, 494-503.
- Parshotam, A., & Hewitt, A. E. (1995). Application of the Rothamsted carbon turnover model to soils in degraded semi-arid land in New Zealand. *Environment International*, 21, 693-697.
- Paul, K. I., Polglase, P. J., Nyakuengama, J. G., & Khanna, P. K. (2002). Change in soil carbon following afforestation review *Forest Ecology and Management*, 168, 241-257.
- Pawson, S. M., Brockerhoff, E. G., Meenken, E. D., & Didham, R. K. (2008). Non-native plantation forests as alternative habitat for native forest beetles in a heavily modified landscape. *Biodiversity and Conservation*, 17(5), 1127-1148.
- Pearson, C. P., & Henderson, R. D. (1998). Frequency distributions of annual maximum storm rainfalls in New Zealand. *Journal of Hydrology (NZ)*, 37(1), 19-33.
- Phillips, C., Marden, M., Lambie, S., Watson, A., Ross, C., & Fraser, S. (2013). Observations of below-ground characteristics of young redwood trees (*Sequoia sempervirens*) from two sites in New Zealand – implications for erosion control. *Plant and Soil*, 363(1-2), 33-48.

- Phillips, C., Marden, M., & Rowan, D. (1989). Planning for forestry after Cyclone Bola, a comment. *New Zealand Forestry*, (November), 16-17.
- Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, R., Saffouri, R., & Blair, R. (1995). Environmental and economic costs of soil erosion and conservation benefits *Science*, 267(5201), 1117-1123.
- Pine Manufacturers. (2013). NZ Pine Users Guide: Log quality and conversion. Retrieved 2 March 2013, from <http://www.pine.net.nz/component/content/article/5-technical-specs/85-nz-pine-user-guide>
- Prasannakumar, V., Vijith, H., Abinod, S., & Geetha, N. (2012). Estimation of soil erosion risk within a small mountainous sub-watershed in Kerala, India, using Revised Universal Soil Loss Equation (RUSLE) and geo-information technology. *Geoscience Frontiers*, 3(2), 209-215.
- Restrepo, C., Vitousek, P., & Neville, P. (2003). Landslides significantly alter land cover and the distribution of biomass: An example from the Ninole ridges of Hawai'i. *Plant Ecology*, 166(1), 131-143.
- Rosser, B. J., & Ross, C. W. (2011). Recovery of pasture production and soil properties on soil slip scars in erodible siltstone hill country, Wairarapa, New Zealand. *New Zealand Journal of Agricultural Research*, 54(1), 23-44.
- Salinger, M. J., & Mullan, A. B. (1999). New Zealand climate: temperature and precipitation variations and their links with atmospheric circulation 1930-1994. *International Journal of Climatology*, 19, 1049-1071.
- Schicker, R., & Moon, V. (2012). Comparison of bivariate and multivariate statistical approaches in landslide susceptibility mapping at a regional scale *Geomorphology*, 161-162, 40-57.
- Selby, M. J. (1993). *Hillslope Materials and Processes*, (2<sup>nd</sup> ed), New York: Oxford University Press.
- Serengil, Y., Swank, W. T., Riedel, M. S., & Vose, J. M. (2011). Conversion to pine: Changes in timing and magnitude of high and low flows. *Scandinavian Journal of Forest Research*, 26(6), 568-575.
- Smith, R. B., Commandeur, P. R., & Ryan, M. W. (1986). Soils, vegetation, and forest growth on landslides and surrounding logged and old-growth areas on the Queen Charlotte Islands. Victoria, B.C: Land Management Report No. 41. Canadian Forestry Service.

- Sparling, G., Ross, D., Trustrum, N., Arnold, G., West, A., Speir, T., & Schipper, L. (2003). Recovery of topsoil characteristics after landslip erosion in dry hill country of New Zealand, and a test of the space-for-time hypothesis. *Soil Biology and Biochemistry*, 35(12), 1575-1586.
- The Economics of Ecosystems and Biodiversity (TEEB). (2010). Mainstreaming the Economics of Nature: a Synthesis of the Approach, Conclusions and Recommendations of The Economics of Ecosystems and Biodiversity. Retrieved 6 March 2013, from <http://www.teebweb.org/publications/teeb-study-reports/synthesis/>
- Thompson, C. S. (1987). The climate and weather of Hawke's Bay. Series 115 (5) New Zealand Meteorological Service, Wellington.
- Trustrum, N. A., Lambert, M. G., & Thomas, V. J. (1983, January 1983). *The impact of soil erosion on hill country pasture production in New Zealand*. Paper presented at the Second International Conference on Soil Erosion and Conservation, Honolulu, Hawaii.
- Turner, J., & Lambert, M. J. (2011). Analysis of nutrient depletion in a radiata pine plantation. *Forest Ecology and Management*, 262(8), 1327-1336.
- West, G. G., Moore, J. R., Shula, R. G., Harrington, J. J., Snook, J., Gordon, J. A., & Riordan, M. P. (2012). *Forest management DSS development in New Zealand*. Paper presented at the 1st International Scientific Conference, Implementation of DSS into the forestry practice, Technical University, 10 May, Zvolen, Slovakia.
- Will, G. M. (1971). Nitrogen supply, apical dominance and branch growth in *Pinus radiata*. *Plant and Soil*, 34, (3) 515-517.
- Will, G. M. (1985). Nutrient deficiencies and fertiliser use in New Zealand exotic forests. *Forest Research Bulletin*, 97.
- Wilmhurst, J. M., Anderson, A. J., Higham, T. F. G., & Worth, T. H. (2008). Dating the late prehistoric dispersal of Polynesians to New Zealand using the commensal Pacific rat. *Proceedings of the National Academy of Sciences of the United States of America*, 105(22), 5.
- Wischmeier, W. H., & Smith, D. D. (1978). *Predicting rainfall erosion losses. A guide to conservation planning, agricultural handbook 537*, Washington, DC: US Department of Agriculture.
- Woollons, R. C., & Manley, B. R. (2012). Examining growth dynamics of *Pinus radiata* plantations at old ages in New Zealand. *Forestry*, 85(1), 79-86.

Woollons, R. C., Skinner, M. F., Richardson, B., & Rijske, W. C. (2002). Utility of "A" horizon soil characteristics to separate pedological groupings, and their influence with climatic and topographic variables on *Pinus radiata* height growth. *New Zealand Journal of Forestry Science*, 32(2), 195-207.

## Chapter Five: Conclusions

---

### 5.1 Introduction

The aim to of this thesis was to investigate the impact of soil erosion on forest productivity of *Pinus radiata* plantation forestry in a catchment (Pakuratahi) comprising mainly hilly to steep land in Hawke's Bay on the east coast of the North Island, New Zealand. *Pinus radiata* trees grown on both eroded and non-eroded sites were measured and associated soils, dominantly Pallic and Pumice soils together with subordinate Recent soils (Hewitt, 2010), were analysed from both sites to enable comparisons to be made. Chapters 2 to 4 each addressed one of three objectives outlined in Chapter 1. The key findings of each chapter are summarised below followed by recommendations for future research.

The three main objectives set to achieve this aim were to:

1. measure the difference between soil properties in eroded (slipped) and non-eroded (non-slipped) land under plantation forest and determine the effects on forest productivity (Chapter 2);
2. estimate soil and nutrient loss at catchment scale using LiDAR and GIS (Chapter 3);
3. investigate the potential for reduced productivity across Hawke's Bay in plantation forest planted since the Cyclone Bola event in 1988 (Chapter 4).

### 5.2 Summary and Conclusions

#### *5.2.1 Impacts of shallow landslide erosion on forest productivity*

The objective addressed in Chapter 2 was to determine the impact of soil physical and chemical properties on *Pinus radiata* productivity. Results from soil analysis and forest mensuration were statistically analysed using Microsoft Office Excel, (2007). Paired *t*-tests for sample means were used to test for significant differences in soil properties, and average tree size across the eroded and non-eroded sites. Regression analysis was carried out to determine any relationships between measured soil properties and tree volumes. Growth simulation software, Atlas Forecaster, was used to estimate the economic/return value of the trees measured in this trial. The key findings of Chapter 2 were:

- Selected soil properties measured at eroded sites were significantly less than the same properties at non-eroded sites: soil N (52% less), soil C (47%), soil P (43%), C: N ratio (8%), soil pH (3%), and mean soil depth (16%)
- Regression analysis showed that volume in trees was significantly correlated with reduced amounts of total C, total N, total P and soil organic matter
- High quality pruned logs for a 25 year rotation were valued at 9% less in eroded plots for total recoverable volume, with a reduction in total recoverable revenue at \$7,500 per hectare.

### *5.2.2 Estimating soil and nutrient loss in Pakuratahi*

The objective addressed in Chapter 3 was to calculate soil and nutrient loss from eroded sites in Pakuratahi and to estimate potential losses from historical and future erosion events.

The key outcomes of Chapter 3 were:

- At a depth of 0.1 m, it was estimated that the average loss per plot from erosion was 22 tonnes (t) of soil, 0.5 t of C, 0.034 t of N and 0.005 t of P
- For all slips mapped across Pakuratahi (12 ha out of 774 ha in total), soil and nutrient loss equates to 2385 t of soil, 271 t of C, 20 t of N and 3 t of P
- Using a non-linear regression model, it was estimated that ~1 km<sup>2</sup> and ~3 km<sup>2</sup> of land in Pakuratahi would be at high risk of erosion, following an 80- year and a 100-year extreme rainfall event, with associated soil losses of 2630 t and 7890t, respectively

### *5.2.3 Regional effects on forest productivity following extreme rainfall events*

The objective addressed in Chapter 4 was to identify terrain in the Hawke's Bay that was comparable to that of the Pakuratahi catchment in order to gain an understanding of costs and benefits to forestry for planting on potentially erodible soils. The key outcomes of Chapter 4 were:

- 65 km<sup>2</sup> were identified as having terrain attributes similar to those at Pakuratahi
- Up to 169,000 t of soil could be potentially lost following an extreme rainfall event
- The value of the service provided by land owners through avoided erosion or erosion mitigation is around \$288 per t of soil
- The value of ecosystem services provided by forestry is not currently recognised financially in New Zealand.

Afforestation of potentially erodible soils has been shown to reduce the incidence of erosion. However, trees grown on eroded slopes tend to be smaller in volume and produce reduced financial returns. Losses of soil and nutrients were calculated for Pakuratahi. An estimate of potential value of avoided erosion was identified for erodible soils in Hawke's Bay which have similar terrain attributes. The estimated costs are largely conservative as this analysis does not take into account other potentially erodible soil types throughout the Hawke's Bay region. Currently the cost of maintaining viable production of erodible hill country has been borne by the forest owner/manager. The value of the ecosystem services provided by forestry is not yet recognised financially in New Zealand.

### 5.3 Further Research

Forestry is increasingly venturing onto marginal lands while at the same time being made accountable for sustainable practices. Additional field studies on a catchment basis are needed to provide raw data across a range of differing forested environments in New Zealand. Data such as these would help quantify the extent of the ecosystem services forestry provides. Developing a framework that identifies the costs and benefits both financially and environmentally would in turn aid policy planning in erosion mitigation where marginal land can be used productively and sustainably.

## Appendix A

---

Soil profile Pakuratahi: scarp wall between eroded and non-eroded plot

**Profile** – *Pinus radiata*

**Reference data**

- Soil classification:
  - NZSC: Typic Immature Pallic Soils



**Figure A1.** Soil profile described in Typic Immature Pallic Soils

## Site data

- Location:
  - NZTM 1932098 5640357
  - profile located ~ 5 m from centre of plot 27 Pakuratahi forest, 21 km north west of Napier
- Elevation: 309 m asl
- Geomorphic position: Profile on edge of slip wall on concave spur of steep gully in hill country
- Erosion/Deposition: Active
- Vegetation: Fern and blackberry undergrowth amongst *Pinus radiata*
- Parent material: Tephra over sedimentary conglomerate (Eyles and Fahey, 2006)
- Drainage class: Moderately well drained

## Soil data

### Ah

0-16 cm Slightly moist, black (10 YR 2/1) very slightly gravelly sandy loam with fine fresh, sub-rounded, sedimentary gravels; slightly sticky, slightly plastic; peds weak and friable; moderate, common fine polyhedral peds; many, extremely fine and very fine, ubiquitous, woody and fibrous roots; moderately allophanic; distinct, smooth boundary.

### Bw1

16-27 cm Slightly moist; very dark brown (10YR 3/2) very slightly gravelly, sandy loam with fine, slightly weathered, sub-angular pumice gravels; slightly sticky; slightly plastic; peds weak and friable; few, weakly, fine polyhedral peds; few microfine, ubiquitous, woody and fibrous roots; strongly allophanic; distinct wavy boundary.

### Bw2

27-49 Slightly moist; brown (10YR4/3) very slightly gravelly, sandy loam with fine, slightly weathered, sub-angular pumice gravels; slightly sticky, slightly plastic; apedal, massive; few microfine and very fine ubiquitous, woody and fibrous roots; strongly allophanic; indistinct boundary.

Bw3

49-69 Slightly moist; brown (10YR 5/3) very slightly gravelly, sandy loam with fine, fresh sub-rounded sedimentary and pumice gravels; slightly sticky; slightly plastic; apedal massive; few extremely fine and very fine ubiquitous woody and fibrous roots; moderately allophanic; indistinct boundary.

bBC(f)

69 – on Slightly moist; yellowish brown (10YR 5/4) and pale brown (10YR 6/3) slightly gravelly, sandy loam with medium fresh sub-rounded sedimentary gravels; slightly sticky; non plastic; apedal massive; few, very fine, distinct, strong brown (7.5 YR 4/6) mottles; few very fine ubiquitous, woody roots; weakly allophanic.

## Appendix B

---

Soil profile Pakuratahi: within eroded plot

Profile - *Pinus Radiata*

### Reference data

- Soil classification:
  - NZSC: Typic Tephric Recent Soil



**Figure B1.** Soil profile described in Typic Tephric Recent Soil

## Site data

- Location:
  - NZTM: 193209 564035
  - profile located ~ 2 m from centre of Plot 27 in Pakuratahi Forest
- Elevation: 308 m asl
- Geomorphic position: Profile in centre of earth slip on the sides of a gully in steep hill country
- Erosion/Deposition: Active
- Vegetation: Fern undergrowth amongst *Pinus radiata*
- Parent material: Sedimentary conglomerate
- Drainage class: moderately well drained
- Comment: Soil is very mixed

## Soil data

L

2 mm

FH

BC(f)

0-40 cm Slightly moist, olive brown (2.5 Y 4/3) and black (2.5 Y 2.5/1) and light yellowish brown (2.5 Y 6/4) slightly gravelly sandy loam with fine to medium fresh, sub-rounded gravels; few, extremely fine strong brown (7.5 YR 4/6) segregated concentrations; slightly sticky; moderately plastic; soil weak; apedal massive; few, very fine, faint, strong brown (7.5 YR 4/6) mottles; very fine, common, extremely fine, very fine, fine, medium and coarse ubiquitous, woody roots; non- allophanic; sharp, smooth boundary.

1bAB

40-55 cm

(15 cm) Slightly moist, very dark, greyish brown (2.5 Y 3/2) and olive brown (2.5 Y 4/3) slightly gravelly sandy loam with fine, medium and coarse, fresh sub-rounded gravels; slightly sticky; slightly plastic; soil weak; peds weak and friable; moderately pedal with many medium polyhedral peds; very few, very fine, dark yellowish brown (10 YR 4/6) mottles; few extremely fine and very

fine ubiquitous woody roots; very weakly allophanic; abrupt, irregular boundary.

2bBC(f)1

55-73 cm Moist, dark yellowish brown (10 YR 4/4) and olive brown (2.5 Y 4/4) moderately gravelly, sandy loam with fine and medium, fresh, sub-rounded gravels; moderately sticky; moderately plastic; soil weak, apedal massive; common fine and very fine, prominent, strong brown (7.5 YR 4/6) mottles; few, extremely fine, ubiquitous woody roots; non allophanic; distinct, wavy boundary.

2bBC(f)2

73 cm – on Moist, dark yellowish brown (10 YR 3/4) and olive brown (2.5 Y 4/4) moderately gravelly, loamy sand with fine, fresh, sub-rounded gravels; moderately sticky; moderately plastic; soil firm; apedal massive; common, very fine and medium, prominent, dark brown (7.5 YR 3/4) mottles; few, extremely fine, ubiquitous woody roots; non allophanic.

## Appendix C

---

Soil profile Pakuratahi: non eroded control plot

Profile – *Pinus radiata*

### Reference data

- Soil classification:
  - NZSC: Weathered Orthic Recent Soil



**Figure C1.** Soil profile described in the Weathered Orthic Recent Soil

## Site data

- Location:
  - NZTM 1932116 5640349
  - profile located ~ 2 m from centre of plot 28 Pakuratahi forest, north of Napier
- Elevation: 315 m asl
- Geomorphic position: Profile concave spur of steep (24°) gully in hill country
- Erosion/Deposition: Inactive
- Vegetation: grass, fern and blackberry undergrowth amongst *Pinus radiata*
- Parent material: Tephra and sedimentary conglomerate (Eyles and Fahey, 2006)
- Drainage class: Moderately well drained

## Soil data

### A

0-14 cm      Dry, black (10 YR 2/1) non gravelly sandy loam; slightly sticky; non plastic; peds weak and friable; moderately abundant, fine, polyhedral peds; many extremely fine and very fine ubiquitous, woody and fibrous roots; moderately allophanic; abrupt smooth boundary.

### AB

14-26 cm      Dry, dark greyish brown (10YR 4/2) very slightly gravelly sandy loam, with medium slightly weathered sub-rounded gravels; slightly sticky; slightly plastic; peds weak and friable; many, moderately fine, polyhedral peds; few strong brown (7.5 YR 4/6) segregated concentrations; many extremely fine and very fine ubiquitous woody and fibrous roots; very strongly allophanic; distinct, wavy boundary.

Bw

26-35 cm Slightly moist, greyish brown (10YR 5/2) and yellowish brown (10YR 5/4) very slightly gravelly sandy loam, with moderately fine and medium sub rounded gravels; slightly sticky; slightly plastic; apedal massive; few, very fine, strong brown (7.5 YR 4/6) segregated concentrations; few extra fine, ubiquitous woody and fibrous roots; very strongly allophanic; distinct wavy boundary.

bBC

35-59 cm Slightly moist, pale brown (10 YR 6/3) moderately gravelly sandy loam with fresh, fine, medium, coarse and very coarse sub-rounded gravels; slightly sticky; non plastic; apedal massive; few, very fine, strong brown (7.5 YR 5/8) segregated concentrations; few, extra fine, yellowish brown (10 YR 5/8) faint mottles; few, microfine, ubiquitous woody roots; weakly allophanic; indistinct smooth boundary.

Cu

59 – on cm Moist, yellowish brown (10 YR 5/4) very slightly gravelly, loamy sand with fresh, fine sub-rounded gravels; slightly sticky; non plastic; apedal massive; few very fine, ubiquitous woody roots; weakly allophanic.