Using Si-Rich Compounds to Facilitate the Economic and Water Quality Aspirations of Māori Landowners

John Campbell

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Faculty of Health and Environmental Sciences

School of Science

Auckland University of Technology

ABSTRACT

The leaching of nutrients can have a significantly negative effect on the quality and biodiversity of natural waters (Liu et al., 2019). The leaching of nutrients applied to farmland as fertiliser is a leading cause of reduced water quality and biodiversity in the freshwater ecosystems of Aotearoa-New Zealand (Gluckman, Bardsley, et al., 2017). Of the rivers that are located in the pastoral areas of Aotearoa-New Zealand up to 90.0% exceed the Australian and New Zealand Guidelines for Fresh and Marine Water Quality standards (Statistics, 2019). In an attempt to reduce nutrient leaching from farmland more than 50 nutrient leaching mitigation strategies have been used in Aotearoa-New Zealand (McDowell, 2013). Despite the use of these mitigation strategies, nutrient leaching trends for both nitrogen (N) and phosphorus (P) have been worsening over the last decade (Ministry for the Environment & Stats NZ, 2020). Some of the strategies used in Aotearoa-New Zealand have inherent problems. These problems can be summarised as the high cost, the length of time it takes to achieve water quality objectives and the harm that can be caused to other features of the environment (McDowell, 2013).

The leaching of nutrients is a significant cultural issue for Māori landowners due to the responsibilities and obligations of kaitiakitanga. The inherent problems with many of the mitigation strategies make them incompatible with the social and economic imperatives of kaitiakitanga (Forster, 2012; Morgan, 2008). This incompatibility heightens the issue for Māori by limiting their ability to reduce nutrient leaching from within a culturally appropriate framework. The kaitiakitanga practices of early Māori were developed through experience and observation of the natural environment (Marsden & Henare, 1992). Among them was the use of silicon (Si) rich compounds in their food growing and land management practices (Burtenshaw, 2010, Roskruge, 2011). Because early Māori did not experience nutrient leaching at the volume of contemporary farming these traditional practices do not address nutrient leaching. However, the use of Si-rich compounds in modern agriculture has been shown to improve farming productivity and reduce environmental harm including the leaching of N and P (Laing et al., 2006; Matichenkov et al., 2005; Snyder et al., 2016).

A series of pot trials, column experiments and financial analyses were used to determine the suitability of Si-rich compounds for mitigating N and P leaching and their compatibility with the principles and values of kaitiakitanga. Pot trials were used to determine the physical and economic effect of Si-rich compounds on crop yield, fertiliser efficiency, P fixation, soil pH and aluminium (Al) toxicity. The column experiments were used to determine the ability of the Si-rich compounds to reduce N and P leaching and to hold these nutrients in the soil in a plant-available form.

The data collected from the analysis, trials and experiments showed that Si-rich compounds reduced ammonium-N and nitrate-N leaching by up to 72.0% and 85.0% respectively. Phosphorus leaching was also reduced by up to 95.0%. The economic and social imperatives of kaitiakitanga were also met through increased crop yield, reduced expenditure, and no environmental harm.

TABLE OF CONTENTS

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

CHAPTER FOUR

CHAPTER FIVE

CHAPTER SIX

LIST OF FIGURES

LIST OF MAPS

LIST OF TABLES

ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published by another person, nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed:

John Campbell

Date: 08/03/2022

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CHAPTER ONE

Introduction

E tangi ana ngā reanga o uta, e mahara ana ngā reanga a tai mā ta aha rā e whakamahana taku or kia tina.

When the land, river and sea creatures are in distress then I have nothing to be proud of.

1.1 Background

The technological advancements of the Green Revolution (GR) resulted in an unprecedented increase in crop yield and food production throughout the world (Khush, 2001). Up to 1960, it had taken the world almost 10,000 years to produce one billion tonnes of food grain. With GR advancements it took only 40.0 years, from 1960 to 2000, to produce the second billion (Khush, 2001). Between 1960 and 2000, crop yield per hectare of land increased for all developing countries with an average increase in wheat yield of 208.0%, rice increasing by 109.0%, maize increasing by 157.0%, and potatoes and cassava increasing by 78.0% and 36.0% respectively (Pingali, 2012). The ability to increase crop yield so significantly saw the adoption of GR technologies throughout the world, including New Zealand (Britney, 2008; Pingali, 2012). One of the key technologies of the GR that impacted on crop yield was the use of chemical fertiliser in a significantly greater volume than had typically been used previously (Fitzgerald-Moore & Parai, 1996).

The application of nutrients, particularly nitrogen (N) and phosphorus (P) is a critical component of farming productivity and the economy of New Zealand (Williams, 2004; Journeaux et al., 2019). A productive farming industry is vital to the New Zealand economy with dairy alone contributing more to the Gross Domestic Product (GDP) than the fishing, forestry, and mining sectors combined (Schilling et al., 2010). Fertiliser is the largest single fixed cost for sheep and beef farming and the second largest for Dairy farming (Grafton & Manning, 2017). These costs represent 22.0% and 13.0% of the total expenses for sheep and beef and dairy respectively (Fitzgerald, 2016). Despite the cost to farmers, it is common for New Zealand agricultural soils to have higher than scientifically recommended nutrient levels. The practice of over-applying nutrients is considered by some farmers as a safeguard against under-fertilising (Mackay et al., 2009).

The leaching of nutrients from excessively applied fertilisers into groundwater and waterways can have a significantly negative effect on the quality of natural waters (Liu et al., 2019; Smith, 2003; Wang & Li, 2019). Excess N and P in water bodies is a root cause of toxic cyanobacterial blooms (Smith et al., 2016). Cyanobacterial toxins are harmful to aquatic life and can pose a major risk to human health from both oral and nasal ingestion (Wood & Dietrich, 2011).

The amount of applied fertiliser that is leached into groundwater depends on several factors including fertiliser management practices, irrigation management, the type of crop, climate, and the physical and chemical properties of the soil (Bender et al., 2015; Ghiberto et al., 2015; Liang et al., 2011; Maharjan et al., 2014; Siyal et al., 2012; Wang et al., 2015). Depending on the factors that are present, the amount of fertiliser lost through leaching can range from 1.0 – 80.0% of the total amount of applied fertiliser (Bechmann et al., 2012; Matichenkov et al., 2005; Wang et al., 2014; Zhao et al., 2011). The leaching of nutrients applied as fertiliser is responsible, at least in part, for a reduction in farm profitability through a loss in crop and pasture yield, and the overuse of fertiliser (Good & Beatty, 2011; Innes, 2013; Moreno-Seceña et al., 2011).

The leaching of N and P is the greatest concern of all nutrients because both are required to support aquatic plant growth, including algae, and are the key limiting nutrients in aquatic ecosystems (Conley et al., 2009). Poor water quality, as a result of N and P leaching, is a significant environmental problem in New Zealand (Gluckman et al., 2017). As the area of farmland increases, the concentration of nutrients in rivers also increases with up to 90.0% of Aotearoa-New Zealand’s total river length that is located in pastoral areas exceeds the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG) standards. In comparison, only 30.0% of the total river length that is located in native land-cover areas exceed ANZG standards (Statistics, 2019).

1.2 Māori Landowners and Farming

Kaitiakitanga is a cultural responsibility that requires Māori to support and protect the physical and spiritual well-being of the environment and its natural resources including land and water (Roberts et al., 1995). The responsibility of kaitiakitanga extends to water quality and nutrient leaching issues (Te Aho, 2011; Tanner et al., 2017). Māori landowners have expressed a strong desire to fulfil their role as kaitiaki by being “guardians” and “caretakers” of the environment and its natural resources and ensuring that the resources are passed to future generations in a healthy condition (Dewes et al., 2011; Phillips et al., 2016). Māori landowners have also expressed the need to balance the responsibilities of kaitiakitanga with economic imperatives (Cortes-Acosta, 2019; Phillips et al., 2014). While landowners in general face barriers to achieving environmental and economic aspirations associated with their land, Māori landowners face barriers that are unique to Māori. These unique barriers include multiple ownership of land, land tenure, an ever-expanding shareholder base, legislation that constrains management and administration, land succession, internal political factors, governance and environmental factors (Bird, 2012; Clough, 2011; Dewes et al., 2011; Kingi, 2000; McLean, 2002; Ministry of Agriculture and Forestry, 2011; Phillips et al., 2014; White, 1997).

The implementation of strategies that would achieve kaitiakitanga aspirations concerning nutrient leaching and water quality typically requires substantial capital investment (McDowell et al., 2013). However, many Māori landowners lack available capital (Mercer, 2021; Phillips et al., 2016) therefore making the implementation and use of kaitiakitanga based strategies difficult. The ability to raise capital from institutional sources is largely dependent on the profitability of the farming enterprise (Phillips et al., 2014). However, Māori farming enterprises face unique barriers to profitability with Māori land generally being low quality and having a lower than average natural level of fertility (Mercer., 2021; Phillips et al., 2014). 80.0% of Māori land falls into the poorest land classes, supports a limited range of uses and/or is in remote areas, and up to 30.0% of it is landlocked (Ministry of Agriculture and Forestry, 2011; Mercer., 2021). The low quality of the majority of Māori is due, at least in part, to the legacy of land confiscation wherein the best quality land was specifically chosen for confiscation leaving Māori with substandard farming land (Clydesdale, 2007; O'Malley, 2016).

Farm profitability is a barrier to accessing capital from institutional sources for all farmers not just Māori, but Māori face “de facto institutional barriers to capital” that non-Māori do not (Funk et al., 2014, p. 8). Farming is not the only industry where Māori struggle to access institutional capital, with two of every five Māori businesses, companies and joint-venture enterprises struggling with the issue (ANZ Bank, 2014).

It has been acknowledged by Māori leadership, that in general Māori farming enterprises are underperforming (Phillips et al., 2014). For example, Māori dairy farms were less profitable and less productive than similar farms in their region during the years 2006-2010 (Clough, 2011). The lower profitability was due, at least in part, to several factors that are common throughout Māori farming. These factors include lower quality land and lower land use capability, both of which contribute to the higher overhead cost of Māori farms (Phillips et al., 2014). Evidence suggests that Māori farmers will do everything they can to fulfil their role as kaitiaki but without access to capital and a farm that is profitable this is difficult to achieve (Phillips et al., 2014).

In order to increase land productivity and revenue, industry advisers have encouraged Māori to use their land for more intensive and profitable farming practices (Price Waterhouse Coopers, 2013). However, land-use change can require a significant capital investment which in turn will limit alternate land-use options for Māori due to the disproportionate difficulty they have in obtaining capital. Moving into alternate land-use operations is extremely difficult if not impossible for all farming types with the possible exception of carbon farming without investment capital (Cortes-Acosta, 2019; Price Waterhouse Coopers, 2013; Phillips et al., 2016).

Even if the land-use conversion is economically possible, some recommended changes are not compatible with kaitiakitanga because they can cause harm to the environment. For example, dairy farming, which is a frequently recommended land-use change for Māori farmers (Price Waterhouse Coopers, 2013), is widely acknowledged as the single biggest agricultural contributor to water pollution in New Zealand (Foote et al., 2015; Howard-Williams et al., 2010). Although an increase in land productivity and revenue can be achieved through conversion to dairy farming (McCarthy, 2004), the increased revenue might not eventuate for several years (Rowarth, 2013). Nutrient leaching from dairy farms was more than three and half times that of beef cattle and more than four times that of sheep farms (Stats NZ, 2019). Dairy cattle contribute more than twice the amount of nitrate-N per head as beef cattle. In 2017 130,000 tonnes of nitrate-N was leached from 6,529,811 dairy cattle compared to 37,000 tonnes from 3,616,091 beef cattle, and 30,000 tonnes from

27,526,537 sheep (Stats NZ, 2019a; Stats NZ, 2021a). If conventional dairy farming practices are followed, conversion to this farming system could increase the availability of capital. However, a conventional dairy farming system will also increase the volume of nutrient leaching and therefore the amount of capital that will be needed to mitigate the greater volume of leached nutrients. It has also been shown that conversion from less productive farming models can be too expensive (Journeaux, 2019). Converting to dairying from forestry is considered too expensive in most situations and only marginal for sheep and beef, while both conversions will result in an increase in N leaching by up to 2,300.0% for forestry and up to 500.0% for sheep and beef (Journeaux, 2019).

1.3 Nutrient Leaching and Kaitiakitanga

A large number of nutrient leaching mitigation strategies have been developed and recommended for use in New Zealand. In a report prepared for the Ministry for the Environment in 2013, a comprehensive list of leaching mitigation strategies that are recommended and used in New Zealand were discussed (McDowell et al., 2013). Unfortunately, many of the strategies had problems that made them totally unsuitable for use by Māori landowners. McDowell (2013) identified three overarching problems with the leaching strategies:

1. The cost of implementing and using the strategies.
2. The length of time it can take to achieve results.
3. Some of the strategies can cause environmental harm.

The report also points out that it was unlikely that any single strategy would be effective enough on its own to meet a single water quality objective thereby requiring more than one strategy to be implemented and paid for (McDowell et al., 2013). Some of the leaching mitigation strategies are potentially harmful to ecosystems and are therefore in conflict with the principles of kaitiakitanga (Collins, 2011; Smith et al., 2016). Kaitiakitanga encompasses cultural, spiritual, social, and economic imperatives, and its practical implementation and utilisation are impacted heavily by the availability of capital. With these factors in mind, the problems associated with the mitigation strategies, as identified by McDowell (2013), render many of the strategies as being incompatible with the aspirations of Māori landowners and kaitiakitanga.

The principles and values of traditional kaitiakitanga were developed over hundreds of years and were based on the experiential and observational understanding of the natural environment (Marsden & Henare, 1992). However, nutrient leaching at the magnitude experienced by contemporary agriculture did not form any part of Māori experience or observation and therefore the practical tools of traditional kaitiakitanga are not suitable as a solution for contemporary leaching problems. According to Walker (2012, p.4) the tools that are available to contemporary Māori for environmental protection and restoration "are in the voice of western science so the indigenous voice often goes unheard". The unheard Māori voice is seen in the issues that render the strategies outlined by McDowell (2012) as incompatible with kaitiakitanga.

The last 20 years have seen Māori use their own voice to develop a large number of environmental models, frameworks and tools. These tools align and are consistent with the traditional values and principles of kaitiakitanga and are presented and used in a way that makes them coherent with science and to non-Māori and the wider community (Harmsworth et al., 2016; Walker, 2012). A summary of the more commonly used tools is provided in Table 1.

The environmental tools provide information to iwi, hapū, landowners, local councils and communities to help them understand the condition of, the impacts on, and the management of freshwater ecosystems (Harmsworth et al., 2015). What the tools do not provide are target mitigation strategies that, unlike the strategies discussed by McDowell (2013), correspond to the principles and values of kaitiakitanga and meet the aspirations of Māori landowners.

The overarching objective of this study is to fill the gap that exists between the currently available nutrient leaching mitigation strategies and the aspirations of Māori landowners. This objective will be met through the use of a silicon (Si) based strategy that will act as a target mitigation tool in a manner that will meet both the kaitiakitanga and the economic aspirations of Māori landowners.

Table1: *Māori Environmental Tools*

Tool	Type	Reference
Cultural Health Index	Monitoring	Harmsworth et al. 2015
Cultural Health Index for Estuaries	Monitoring	Nelson and Tipa 2012
Cultural Indicators for Wetlands	Monitoring	Nelson and Tipa 2012
Cultural Maine Health Index	Monitoring	Nelson and Tipa 2012
Ngā Waihotanga Iho	Monitoring	Harmsworth et al. 2015
State of Takiwa Toolbox	Monitoring	Nelson and Tipa 2012
Cultural Mapping	Information	Rainforth and Harmsworth 2019
Geographic Info Systems	Information	Rainforth and Harmsworth 2019
Kaitiaki Tools	Information	Harmsworth et al. 2015
Mauri Compass	Information	Rainforth and Harmsworth 2019
Mauri Model	Assessment	Nelson and Tipa 2012
Mauri of Waterways Kete	Assessment	Nelson and Tipa 2012
RIVAS	Assessment	Nelson and Tipa 2012
Wai Ora Wai Māori	Assessment	Rainforth and Harmsworth 2019

1.3 Silicon, Agriculture and the Environment

Compounds that are rich in Si can be used as a highly effective multi-target strategy to reduce nutrient leaching from farmland (Bocharnikova & Matichenkov, 2010). Si-rich compounds can also overcome the three problems identified by McDowell (2013). First, there are several low cost commercially available Si-rich products and this fact coupled with the potential economic benefits achieved through an increase in crop yield and a reduction in fertiliser inputs overcomes the problem of cost (Matichenkov et al., 2005; Matichenkov, 2019). Second, Si-rich compounds can reduce nutrient leaching, by up to 80%, within a single farming season thereby producing results quickly and overcoming the problem of the time it takes to achieve objectives (Matichenkov et al., 2005). Third, although crystalline silica is a carcinogen and hazardous, Si-rich compounds that are suitable for use as a fertiliser and leaching mitigation are in an amorphous form and are typically not harmful to the environment which overcomes the problem of creating or worsening environmental problems (Laane, 2018; Michel et al., 2013; Sekifuji & Tateda, 2019). Silicon-rich compounds, which are suitable for use as fertiliser and leaching mitigation, correspond to the values of kaitiakitanga as evidenced by the common use of Si-rich compounds in traditional Māori crop production (Best, 1930; Furey, 2006; Roskruge, 2011).

The use of Si-rich compounds in agriculture dates back to the 1st century in Asia (Datnoff et al., 1997) and the middle ages in Europe (Liang et al., 2015). Research concerning the use of Si as an agricultural input dates back to the early 1800s (Davy, 1814; Liang et al., 2015; Liebig & Playfair, 1843). Although many of the functions of Si in agriculture were understood in the 19th century, the potential of Si to address environmental issues was more a by-product or secondary issue to the primary topic of research for another hundred years. It was in the 1980s that ecological research (Cooke et al., 2016), including problems such as aluminium (Al) pollution (Birchall, 1992; Panov et al., 1982), and issues related to nutrient leaching (Rochev et al., 1980) began to focus specifically on Si as the primary research topic. A greater understanding of the role and function of Si in the environment was achieved during this latter period including the important role that Si plays in the health of terrestrial, marine and freshwater ecosystems (Cooke et al., 2016; Sutton et al., 2018)

The use of Si-rich compounds in agriculture has produced some remarkable results including increased crop yield, reduced plant disease, improved soil fertility, increased drought resistance, and increased protection against insects and pests (Laing et al., 2006; Meena et al., 2014; Pozza et al., 2015; Rizwan et al., 2015; Snyder et al., 2016). Equally impressive results have been produced using Si-rich compounds to directly address negative environmental conditions. These results include a reduction in nutrient leaching, reduction in pollutants leaching, and the remediation of polluted land and water (Matichenkov & Campbell, 2019; Matichenkov et al., 2005; Saihua et al., 2016).

Despite the impressive outcomes gained from utilising Si-rich compounds in agriculture and for environmental work, its use is not a mainstream strategy in either field. In agriculture, particularly as it relates to plant biology, the role and function of Si is largely ignored (Keeping & Reynolds, 2009; Ma & Takahashi, 2002). Silicon appears to be ignored because the analytical methodologies for the testing of nutrient essentiality in plants were developed and became standard practice before the evidence concerning the importance of Si was confirmed (Epstein, 2009). Despite the amount of evidence that is available, the element continues to be ignored even when the context calls for attention to it (Epstein, 2009). Although Epstein's statement is more than a decade old, and the body of work concerning Si has grown, it continues to hold true today. Despite Si gaining wider acceptance, its role in the soil and crop production is often ignored by mainstream research and literature (Hao et al., 2022, Katz, 2018, Rizwan et al., 2019).

1.4 Traditional Māori Crop Growing

Pre-European Māori demonstrated a high degree of horticultural skill and knowledge. This was demonstrated by their ability to adapt their horticultural practices to successfully grow tropical crops, such as taro (Colocasia esculenta) and kūmara (Ipomoea batatas) in the temperate climate of Aotearoa (Furey, 2006; Roskruge, 2011). The high degree of skill continued to be demonstrated by post-European Māori who were able to produce yields of European introduced crops, such as wheat (Triticum) and corn (Zea mays), that were comparable to yields produced in the North Sea area of Europe (Horrocks et al., 2008; van Bavel & Thoen, 1999) and superior to those produced in Aotearoa-New Zealand by European settlers before the 1860s (Petrie, 2002).

The adoption of European tools allowed Māori to expand from a largely subsistence-based cultivation and inter-tribal trading system to large and successful commercial endeavours that included international trade (Hargreaves, 1959; Petrie, 2013; Reid & Rout, 2016; Roskruge, 2011). Crops were grown by Māori using a hybrid cultivation methodology that combined traditional Māori practices with European technology in a best-of-both-worlds approach (Hargreaves, 1959; Reid & Rout, 2016).

The crop growing and sustainability practices of Māori included the use of Si-rich compounds, in the form of materials such as wood ash. The use of Si-rich compounds is likely to be one reason why Māori enjoyed fertile soil, quality crops, and used a lesser amount of water for irrigation than European settlers (Best, 1930; Datnoff et al., 2001). The combination of Māori practices, including the use of Si-rich compounds, and European technology helped Māori to become the largest exporter of foodstuffs in Aotearoa-New Zealand and the most dominant economic force in the country (Petrie, 2013). One of the factors that led to a rapid and significant decline in Māori agricultural prowess was the abandonment of the traditional methodised practices of sustainability that included the fallowing of land and the use of Si-rich compounds (Hargreaves, 1959; Hargreaves, 1960; Wood, 2003).

1.5 Research Objectives

The overarching objective of this research is to develop a strategy that can be used by Māori landowners to mitigate the leaching of nutrients, which have been applied to the land as fertiliser, in a way that is fully aligned with their economic aspirations and for their aspirations as kaitiaki of the land, water, and natural resources.

Specifically, the strategy will consist of the use of Si-rich compounds that are applied to the land and a reference tool that will provide details and guidance on how to use the Si-rich compounds and the economic and environmental outcomes that should be expected. The reference tool will allow Māori landowners to quickly identify which option best fits their agricultural (in terms of crop yield), environmental (in terms of N and P leaching), and economic (in terms of cost and revenue) situation and requirements. The reference tool will provide an expected range of agricultural, environmental, and economic outcomes relative to the cost of implementing each option.

The success of the overarching objective is tied strongly to the strategy's ability to achieve economic outcomes. The research will determine if the strategy can produce enough revenue to at least cover 100.0% of the cost of its implementation. To that end, the ability of the Si-rich compounds to reduce farming expenditure by decreasing the volume of N and P fertilisers and soil conditioning inputs being applied to farmland will be investigated. A specific emphasis will be placed on the ability of the Si-rich compounds to completely replace the use of lime. The research will also investigate the ability of the Si-rich compounds to at least maintain crop yield rates despite the reduction of fertiliser and soil conditioning inputs.

The mitigation strategy follows the example of Post-European Māori agriculturalists who adopted a hybrid best-of-both-worlds approach to agriculture. This study's mitigation strategy combines the traditional principles and practices of kaitiakitanga with science. The expectation is that the hybrid approach will produce results that are better than an either-or approach. First, the hybrid approach will reintroduce Māori utilisation of Si-rich compounds as an integral and widespread agricultural and sustainability practice. Second, science will increase the efficiency and effectiveness of the Si-rich compounds to match the scale of the leaching problem in contemporary times.

In order to meet the objectives of this research, 64 pot testss, each with three replications, for a total of 192 tests, were conducted. A column leaching experiment was also conducted and it was comprised of ten tests, each with three replications, for a total of 30 tests.

The pot trials utilised a variety of tests to investigate the capability of Si-rich compounds to:

- Reduce the volume of N, P, and lime inputs required for productive farming.
- Reduce the economic losses that can result from the use of N, P, and lime inputs.
- Maintain, if not increase, farming profitability with the use of Si-rich compounds.

In order to determine the capability of Si-rich compounds to reduce nutrient leaching, input use, and maintain profitability the following tests were conducted:

- Plant biomass comparisons between Si-rich compounds, N, P, and lime inputs.
- Plant biomass comparisons between Si-rich compounds and N and P fertilisers that have been applied to the soil at three different rates.
- Biomass comparison of plants grown in soil enriched with a toxic concentration of Al sulphate ($Al_2 (S0_4)_3$ using Si-rich compounds, N, P, and lime inputs.
- Comparison between Si-Rich compounds, N, P, and lime inputs at regulating soil pH and counteracting the effects of exchangeable Al in soil that has been

enriched with a toxic concentration of Al2(S04)3.

- Tests to compare the ability of Si-rich compounds, N, P, and lime inputs to improve fertiliser efficiency, hold nutrients in the soil and keep them in a plant-available form, and counteract P-fixation.

The column leaching experiments utilised a variety of tests to investigate the capability of Si-rich compounds to:

- Reduce the volume of N and P leaching.

While not a specific objective of this study, a feature of the mitigation strategy is the empowerment of Māori decision making and environmental action at the individual level. The Crown's resource management practices are directed toward achieving Crown objectives and Māori participation can be co-opted by the Crown into activities that are secondary to Māori values and objectives (Forster, 2012). The reference tool can help remove the reliance Māori has on the Crown and industry bodies to implement leaching and water quality strategies particularly when these strategies do not match Māori values and objectives. This ability can allow Māori to exercise some level of mana whenua regarding water quality issues. This is an important personalised feature of the study that can help Māori make their own decisions and realise their own environmental goals for their own land.

1.6 Thesis Outline

The thesis is comprised of six chapters and following this introductory chapter, Chapter Two provides a review of literature that is relevant to this study and provides significantly more detail on the key topics that are introduced in Chapter One. Chapter Two commences with a review of literature that defines the meaning of kaitiakitanga and describes the values and principles of this key cultural practice. Literature concerning the history of the Green Revolution, its worldwide expansion, and its technological advancements is then reviewed. Literature concerning the history of agriculture in Aotearoa-New Zealand, its adoption of Green Revolution technologies, and its expansion through to contemporary times are reviewed. The review continues with literature that details the history and practices of Māori horticulture, its expansion into large-scale commercial agriculture with the introduction of European tools, through to modern times. The history and development of the understanding of the role and function of Si in agriculture and the environment are reviewed through an examination of the relevant scientific literature. Chapter Two concludes with a review of the literature concerning the leaching of nutrients from farmland and its effects on water quality.

Chapter Three outlines the test design and fertiliser protocols of the trials and experiments and the materials and methods used to perform them. The results of the tests are provided in Chapter Four. Chapter Five discusses the results of the tests and determines how aligned they are with the objectives of this study including the aspirations of Māori landowners. The discussion focuses heavily on economic outcomes which form a vital component of this study. The leaching mitigation reference tool is also presented in Chapter Five which then concludes with a discussion on the limitations of the research and areas for further study. Chapter Six provides the conclusion of the study including a brief summary of the study's achievement at meeting its overarching objective.

CHAPTER TWO

Literature Review

2.1 Introduction

The literature review of this thesis is comprised of an examination of the key topics of this study. The review commences by examining the concept and values of kaitiakitanga. This examination will include an abbreviated explanation of te ao Māori (Māori worldview) as it relates to kaitiakitanga and a justification of the definition of kaitiakitanga that is used for this study.

Next, an examination of the Green Revolution will include details of its agricultural advances including the significant increase in the use of fertiliser and impacts the Green Revolution had on the environment. The review of the Green Revolution leads directly into an examination of New Zealand’s agriculture from colonisation until the present day with an emphasis on fertiliser use and the impact that fertiliser has on New Zealand’s water quality. Next, an examination of Māori horticulture will include a historical description of pre-European crop growing practices and the transition to large scale commercial agriculture. The review of Māori agriculture will also include the rise of Māori to economic dominance as a result of their agricultural expansion, then its decline, eventual collapse, and partial recovery following the New Zealand Wars. An examination of traditional kaitiakitanga methodologies that relate directly to the use of Si-rich rich compounds will also be provided.

The literature review will conclude with an examination of Si followed by an examination of nutrient leaching. The examination of Si will provide an explanation of its chemical properties and how these properties affect and benefit agricultural practice, particularly on crop yield, soil conditioning, and fertiliser use. The effects that Si has on these features will also be discussed in the context of how Si can be used to achieve the objectives of this study. The examination of leaching will provide details on why nutrients leaching into water can reduce the water quality and why nutrient leaching occurs. A discussion on water quality in Aotearoa-New Zealand will be followed by a discussion on the leaching mitigation strategies that have been used in Aotearoa-New Zealand and some of the problems that are inherent in these strategies. Finally, how Si can react with nutrients in the soil and how these reactions can reduce nutrient leaching and overcome the problems inherent in other leaching mitigation strategies.

2.2 DEFINING KAITIAKITANGA

> *"If Tūhoe talks to Tūhoe, then we are talking to Te Urewera. You cannot separate the two. We are all around and within it. We have relations here, there and there. And we are all intertwined. Tūhoe and Te Urewera are one. It is incomprehensible to see them as separate."*
>
> - Henare Nikora, Tūhoe

2.2.1 Language Translation

The oral or written translation of a source language to a target language is a complex and problematic process (Al-Hammar, 2019). Aspects of language translation have been described as being one of the most complex issues in the evolution of the cosmos (Brislin, 1976). The complexity is so great that even the use of the most advanced and sophisticated computer applications (machine translation) has not solved long identified problems that the ambiguous nature of language and its translation poses (Maučec & Donaj, 2019).

The problems associated with translation stem from the equivalence of meaning in linguistic issues such as structure, grammar, syntax, pragmatism, idioms and rhetoric between the source and target language (Baker, 2018). Translation, if the goal is to accurately convey the ideas, concepts and meaning of the source language, the outdated practice of providing an as close as possible word-for-word parallel of the target language is not effective (Malinowski, 1994).

In addition to language equivalence the issue of cultural equivalence, where words and phrases are so ingrained and unique to a source culture that there is no equivalent in the target culture, can also pose problems in translation (Fernández Guerra, 2012). Cultural equivalence can be a more serious problem than language equivalence (Nida & Taber, 1982) because in all cases a successful translation will be extremely difficult, and perhaps impossible, to achieve (Fernández Guerra, 2012). Also, cultural translation methodologies are less exacting and scientific than the more rigorous methodologies for linguistic translations (Yengoyan, 2003). Biggs provides examples of translations between the English and Japanese cultures that illustrate the problem wherein the term "grapes of wrath" has been translated as "angry raisin" and "liberty and the pursuit of happiness" has been translated as "licence to commit lustful pleasures" (Biggs, 1989).

2.2.2 Māori Language Translation

The Māori language and culture face the same translation problems presented by language and cultural equivalence. Just like any other source language and source culture the real meaning of Māori language and cultural practice can be corrupted when they are incorporated into the prevailing culture (Roberts et al., 1995). The problem with equivalence is demonstrated by the various English translations of Te Tiriti o Waitangi (Te Tiriti). While translations of Te Tiriti are generally accurate there are problems with key terms where the English word conveys a different meaning than the Māori word. Despite the general accuracy of the translation, the corruption of some key terms can lead to a distortion of Te Tiriti's overall meaning (Mutu, 2010). Te Tiriti has also been subjected to 'translations' that are more concerned with social or political agendas than an accurate representation of meaning. Several issues concerning the 1922 work of Sir Apirana Ngata, Te Tiriti o Waitangi: He Whakamarama, have been raised by several authors as pointed out by Mutu (2010, Ch.1).

> *"Biggs describes Ngata's 'translation' of the Treaty as an apologia, an attempt to dampen down Māori protest at violations of the Treaty rather than to explain its terms. Orange points out that despite being cited as if it were a reliable, authoritative statement of the understanding of Māori in 1840, it is not."*

A linguistic and cultural translation is required when providing an English language definition of the term kaitiakitanga. As with all translations from Māori into English, accurately conveying the meaning of the term kaitiakitanga can be difficult. Several issues add to the normal complexity of the translation process, two of which are chiefly relevant to this study. First, the highly complex nature of kaitiakitanga itself means that the term is highly variable and does not have a single meaning (Kawharu, 2000). Second, much like the social and political climate of the day shaping Ngata's ‘translation’ of Te Tiriti, contemporary issues have shaped translations and definitions of kaitiakitanga.

2.2.3 Linguistic Translation of Kaitiakitanga

Kaitiakitanga is the term used by Māori to define conservation customs and traditions (Marsden & Henare, 1992). A literal translation of the term kaitiakitanga stems from the word “tiaki”, the prefix “kai” and the suffix “tanga”. Tiaki means to guard, and depending on the context of usage it can also mean, among other things, to preserve, to conserve, and to protect. The prefix kai denotes the agent of the act, therefore, if tiaki refers to the act of guarding then kaitiaki is a guardian. The suffix tanga, when added to the noun, gives the meaning of guardianship (Marsden & Henare, 1992). However, while an accurate linguistic translation is possible, the literal translation does not convey the depth or richness of the idea, concept, and meaning of kaitiakitanga as understood within te ao Māori.

2.2.4 Cultural Translation of Kaitiakitanga

The extreme difficulty and even impossibility of a successful cultural translation are epitomised by the term kaitiakitanga. The ideas, concepts and meaning of kaitiakitanga sit within a Māori worldview that is comprised of cosmological and cosmogonical viewpoints. These viewpoints describe what happened before, during and after the creation of the universe, how and why everything was created, and explains the relationship between the Creator, the universe, all non-living things and all living things including human beings (Marsden & Henare, 1992; Roberts et al., 2004; Roberts et al., 1995). It is from these viewpoints and their connectedness with other concepts, that kaitiakitanga can be understood, at least to some degree, beyond the common literally translated definition. The complexity of this worldview defies a generically packaged English translation that fits within a western worldview. The complexity of the worldview is exacerbated by the fact that kaitiakitanga is spiritual in nature and does not have a single perspective that covers all iwi or hapū (Hayes, 1998).

Key concepts of the Māori worldview include ‘whakapapa’ and ‘mauri’ (Reid et al., 2013). Whakapapa represents significantly more than the commonly held understanding of it being a database that recounts lineal ascendants or descent of human ancestors. Whakapapa recounts the kinship that exists between everything in the universe; living and non-living, material and immaterial, human beings and atua (Haami & Roberts, 2002). In general, the traditional Māori view of the entire natural world forms a cosmic family and that the weather, birds, fish and trees, sun and moon all form part of that cosmic family and are related to each other and the people of the land (Royal, 2013). The relationship of the cosmic family is shown through whakapapa which recounts the descent of all living things from the creator parents Ranginui, the sky father, and Papatūānuku, the earth mother who were in turn formed through Io, the source of the creation process (Reid et al., 2013). Mauri is part of the cosmic family and appears in the early stages of whakapapa. Mauri is the life force or energy that permeates through all living and non-living things and makes life possible by sustaining and animating all forms of it (Marsden & Henare, 1992). Mauri denotes a level of health, therefore damage or contamination of a living thing is damage to or loss of mauri (Harmsworth & Awatere, 2013). Loss of mauri can be gauged by its ability to support life. Reid (2013, p.4) describes this feature of mauri in the following way:

> *"…the level of mauri contained by a river can be determined by its capacity to maintain and support life. Through ill-treatment (e.g., pollution), the mauri of the river can decline, which will in turn mean that its capacity to support life will decline."*

If mauri has been damaged or suffered a decline it is still possible for it to be restored (Hikuroa et al., 2011). The possibility for mauri loss and restoration is demonstrated by the Mauri Model which is a framework that adopts mauri as the measure of environmental, economic and cultural well-being. The framework uses a series of steps to determine if mauri has been restored, enhanced, maintained, diminished or destroyed (Morgan, 2008). As pointed out by Morgan (2008) the base metric of kaitiakitanga is mauri, it is the mauri of all living things that is of most value and in need of protection and restoration. Mauri can also be considered from an economic perspective in that the mauri of an ecosystem relates directly to that ecosystem's ability to provide life giving produce both for consumption and for trade. Morgan (2008, p. 63) states that:

> *“Mauri is a measure of valuing things with the end objective being protection of valued aspects of the economic life of the Māori…mauri is a metric that can effectively reflect the well-being of the four dimensions of sustainability identified as environmental, social, economic and cultural well-being.”*

It is common to refer to kaitiakitanga in a resource management context that reflects guardianship of the natural environment and natural resources such as the sea, land, water, mountains, and forests. When contextualised with whakapapa it can be understood that the resources that need to be managed include everything in the universe. Kaitiakitanga is not limited to an environmental ethic, it is a socio-environmental ethic that is concerned about the relationship between humans and the environment, their gods and each other (Kawharu, 2010). Whakapapa also contextualises the responsibility that human beings have to act as the guardians of all things that come from the earth mother Papatūānuku in the same way any child has a responsibility toward a parent and siblings. Marsden and Henare (1992, p. 16) describe the child-mother relationship and associated responsibility:

> *“…just as the foetus is nurtured in the mother’s womb and after the baby’s birth upon her breast, so all life forms are nurtured in the womb of Papatūānuku and upon her breast…He is her son and therefore as every son has social obligations to fulfil towards his parents, sibling and other members of the whanau (family), so has man an obligation to mother earth and her whanau to promote their welfare and good.”*

When kaitiakitanga is contextualised with mauri it can be understood that it is the life force of all things that need to be guarded, managed, and restored when it is damaged or lost (Forster, 2012). The children of Papatūānuku who have the responsibility and obligation to protect her are the minders or kaitiaki of her mauri. The Report and recommendations of the Board of Inquiry into the New Zealand Coastal Policy statement of 1994 (Department of Conservation, 1994) discusses this issue:

> *“…as minders, kaitiaki must ensure that the mauri or life force of their taonga is healthy and strong. A taonga whose life force has been depleted…presents a*

> *major task for the kaitiaki. In order to uphold their mana, the tangata whenua as kaitiaki must do all in their power to restore the mauri of the taonga to its original strength."* (p. 17)

Protection of mauri is necessary, in part because the mauri of a natural system is defenceless against harmful elements that do not naturally belong there, such as farm effluent being discharged into a river (Huakina Development Trust v. Waikato Water Board 1987).

2.2.5 Expedient Translation of Kaitiakitanga

Similar to the political and social expedience of Ngata's translation of Te Tiriti, the term kaitiakitanga has been the subject of expedient translation and definition. As an example, the poor translation and definition of kaitiakitanga in the Resource Management Act 1991 allowed the judicial system to misinterpret kaitiakitanga and therefore judicial outcomes which in turn caused Māori to oppose this statutory definition (Hayes, 1998). The growing discontent and opposition among Māori regarding this definition led to its amendment in 1997 which defined kaitiakitanga as "…the exercise of guardianship by the tangata whenua of an area in accordance with tikanga Māori concerning natural and physical resource; and includes the ethic of stewardship" (New Zealand Government 1991, s 7(a) and 7(aa). However, the political expediency of the definition has reduced the ideas, concepts and meaning of kaitiakitanga to the point that "kaitiakitanga has become almost locked into meaning simply 'guardianship' without understanding of (or in the case of the Crown, providing for) the wider obligations and rights it embraces." (Kawharu 2000, p. 351). Further, 'stewardship' is not an appropriate definition for kaitiakitanga since the original meaning of stewardship is "to guard someone else's property", but the ownership of property was a foreign concept to Māori before European contact (Marsden & Henare, 1992). Kaitiakitanga is not about ownership or control of land or any natural resource. Māori Marsden (Marsden, 2003) states that:

> *"The resources of the earth did not belong to man but rather, man belonged to the earth. Man as well as animal, bird, fish could harvest the bounty of mother earth's resource but they did not own them. Man had but user-rights*." (p.67)

Hayes (1998) also believes that the words ‘stewardship’ and ‘guardianship’ are concerning as both cloak the concept of kaitiakitanga in terms of lesser importance and that the “role of the kaitiaki is considerably more significant than simply that of a guardian or steward. It is a vital component in the spiritual and cultural relationship of tangata whenua with their land. (p. 898)

Before 1997 it had been posited that non-Māori could claim the status of kaitiaki (Hayes, 1998). However, tikanga dictates the status or position of kaitiaki comes from whakapapa and tribal association, and only tangata whenua of the local area can act in that capacity (Minhinnick, 1989). One positive aspect of the 1997 amendment was the statutory agreement with tikanga concerning the status of kaitiaki.

2.2.6 Working Definition of Kaitiakitanga

The description provided above is a basic and abbreviated account of the principles and values of kaitiakitanga. There has deliberately been no description of mana, manaakitanga, or whanaungatanga, all of which are features of the principles and values of kaitiakitanga. Māori can and do disagree on aspects of kaitiakitanga, including the worldview from which environmental values are derived, but there are commonly held fundamental beliefs associated with the concept (Henare, 2001; Patterson, 1994).

Forster (2012) describes a bond that Māori understanding of the environment creates:

> *“This bond is achieved through the cultural precepts of mauri and whakapapa that established an interconnectedness and natural order in the world. All life forms both animate and inanimate are connected and interdependent and it is this bond that regulates the relationships and interactions of Māori with the environment.”* (p. 27)

Rather than providing an exhaustive account of all the features of kaitiakitanga, this study will focus on the commonly held beliefs that regulate the relationship and interactions that Māori has with the environment - mauri and whakapapa. These features provide a framework that is most directly relevant to the objectives of this study. This position is justified for two reasons. First, the primary objective of the study is the design and use of a practical leaching mitigation tool. The protection and restoration of mauri by the mitigation tool is the predominant kaitiakitanga value that is associated with this study. Second, the mitigation tool is designed to be used by individual landowners and it is their aspirations as kaitiaki that are of paramount importance and upon which this study has been designed.

Landowner aspirations have been expressed in formal research. For example, Te Puni Kōrkiri (TPK) published its research on landowner aspirations in the work Ko Ngā Tumanako o Ngā Tanga Whai Whenua Māori: Owner Aspirations Regarding the Utilisation of Māori Land (Dewes et al., 2011). TPK is the government department responsible for advising the New Zealand government on policies and issues that affect Māori. In order to obtain an understanding of the aspirations that Māori landowners have for their land, TPK conducted a research project that included a series of hui where Māori landowners were asked directly about their aspirations. Dewes (2011, p. 15) believes that the participant responses showed that "their aspirations for the land were fundamentally connected to their role as kaitiaki". (p. 15)

One of the strengths of TPK's qualitative approach is that it allowed the landowners to define what they believed kaitiakitanga is, how they viewed their role as kaitiaki and describe the priorities and values they personally place on these concepts (Dewes et al., 2011). The differing perspectives of Māori are explained in the following way (Rangihau, 1975, p. 12. 13, 28):

> *"My being Māori is absolutely dependent on my history as a Tūhoe person…there is no such thing as Māoritanga because Māoritanga is an all-inclusive term which embraces all Māori. And there are so many different aspects about every tribal person. Each tribe has its own history."* (p. 12, 13, 28).

Due to differing tribal views, it is important to see and understand, from the context of each individual's tribal background, their viewpoint concerning kaitiakitanga (Roberts et al., 1995). By allowing its participants to articulate and define their personal views, TPK was able to follow the route to clear understanding suggested by Roberts not only at a tribal but also at the individual level. The value of TPK's finding is found, at least in part, in its qualitative approach. Māori were able to express themselves and their identity, which identity is intrinsically linked to the land, in their own words based on their own perspectives which produced a personalised understanding of their aspirations. This valuable understanding would be challenging to produce using a quantitative methodology (Lockhart et al., 2019). Despite the differences in individuals and tribal affiliations, Māori aspirations were uniform across all hui (Dewes et al., 2011), perhaps due, at least in part, to the bond in cultural precepts of mauri and whakapapa described by Forster.

The participants in the TPK hui explained that their responsibility as kaitiaki was to the previous generations who left them the land and to the following generation who will inherit the land by ensuring it is left to them in an improved state. Therefore, these kaitiaki values and responsibilities were coupled with other aspirations such as the utilisation of land for business purposes. Dewes (2011. P. 17) recounts one participant's description of this aspiration in the following way:

> *"…I don't want it to be a it's either money-making or it's either cultural. I want it to be a big bang of both and that both of those, the cultural and the money thing, are both as equally as important and useful to Māori and not just for today, like forever…".*

Traditional concepts and values form a strong part of contemporary Māori identity and are the basis for their perspectives on issues such as kaitiakitanga (Harmsworth & Awatere, 2013). While the TPK hui participants did not provide a definitive definition of kaitiakitanga or express their understanding of te ao Māori, they did express their personal views, priorities and values which were fashioned by their Māori identity. The participant responses relate directly to the objective of this study, which is to help Māori achieve the aspirations they have for their land, which they identified as environmental and economic.

The aspirational similarities of the TPK hui participants, regardless of tribal affiliation, provide a framework from which to extract a working definition of kaitiakitanga that is specific to the objectives of this study. For the purposes of this study, kaitiakitanga is defined as:

> *"Guardianship, in the form of protection and restoration, of the mauri of Māori farmland and adjoining water bodies, while simultaneously using the land for the economic benefit of tangata whenua."*

The working definition incorporates both a literal and a cultural translation. The terms guardianship, protection and restoration stem from a literal translation. The term mauri is a specific component of the cultural translation that is not found in a literal definition. The working definition is basic but it is also specific and directly addresses the stated aspirations of Māori landowners.

2.3 MODERN AGRICULTURE

"The green revolution has an entirely different meaning to most people in the affluent nations of the privileged world than to those in the developing nations of the forgotten world."

- Norman Borlaug

2.3.1 The Green Revolution

It is generally agreed that the world has experienced three major, or world-changing, agricultural revolutions (Scholten, 2014). The first agricultural revolution referred to as the Neolithic Revolution, started approximately 13,000 years ago with the transition from a forager (hunter-gatherer) society to a producer (farming) society (Bocquet-Appel, 2011). The second agricultural revolution, referred to as the British Agricultural Revolution, resulted in a significant increase in farming output as a result of improved farming practices, increased labour, technological advancement, and increased land productivity (Overton, 1996). There is considerable debate concerning the time of the British Agricultural Revolution, with some academics believing it started as early as the 16th century and others believing it commenced in the 19th century (Allen, 1999). There is a view that a symbiotic relationship existed between the technological improvements of the British Agricultural Revolution and the Industrial Revolution of 1760 - 1840 (Van Neuss, 2015). Although not considered a world-changing revolution, the Arab Agricultural Revolution commenced in the 7th century and changed the Islamic world by introducing new crops and advanced agricultural technologies particularly in irrigation and animal husbandry (Ruggles, 2011; Watson, 1974). The third agricultural revolution, also referred to as the Green Revolution (GR), resulted in a significant increase in crop yield, primarily through genetically modified plant varieties, the high volume use of inorganic fertiliser, agro-chemicals, controlled irrigation, and new farm machinery (Flachs, 2016; Jain, 2010; Pellegrini & Fernández, 2018). The GR is generally considered to have taken place over a period spanning the 1940's to the 1970s (Evenson & Gollin, 2002). The technological momentum of the GR endured into the 21st century and continues to shape contemporary agricultural practices (Parayil, 2003; Pellegrini & Fernández, 2018).

The GR was a deliberately conceived and implemented research and development program that was designed to increase world food production and reduce hunger, particularly Third World hunger. The program received cooperation and support from multiple governments, research agencies, the United Nations, and significant financial and logistical support from philanthropic organisations, most notably the Ford and Rockefeller Foundations (Britney, 2008; Jain, 2010). The organised approach to agricultural research led to the creation of the International Maize and Wheat Improvement Centre (CIMMYT) and the International Rice Research Institute (IRRI), which under the umbrella of the Consultative Group on International Agricultural Research (CGIAR), led and fostered the GR research initiatives (Evenson & Gollin, 2002).

The GR resulted in extraordinary growth in food production. Over a period of 50 years, food production grew by 300.0% and this occurred with an increase in land use of only 30.0% (Pingali, 2012). This level of growth was unprecedented at any time in human history. It took mankind almost 10,000 years to produce 1.0 billion tonnes of food grain, and the next 40 years, from 1960 to 2000, to produce the second billion, and from 2008 to 2009 to produce an additional 2.3 billion tonnes (Khush, 2001; Zimdahl, 2012). During the 40 years between 1969 to 2000, the world population doubled, but this increase was more than matched by global food production which was significantly higher per capita in 2000 than it was in 1960 (Hedden, 2003).

Leading up to and during the early years of the GR several academics had predicted that the world would experience severe famine. Ecologist Paul Ehrlich predicted that famine would be so severe it would cause the greatest cataclysm in the history of mankind and that within a decade Japan would starve and a horde of famished Chinese would invade Russia (Ehrlich et al., 1971). Ehrlich (1971) also stated that:

> *"The battle to feed all of humanity is over. In the 1970s the world will undergo famines – hundreds of millions of people are going to starve to death in spite of any crash programs embarked upon now".* (p. 11)

Ehrlich is often asked what happened to the famines he predicted. Ehrlich's answer is found in a review of his earlier almost 40 years after it was published (Ehrlich & Ehrlich, 2009, p. 9):

> *"What happened? The central factor, of course, was the medium-term success of the "green revolution" in expanding food production at a rate beyond what many, if not most, agricultural experts believed likely".*

The GR was spectacularly successful in keeping food production ahead of the world's population growth. Increased food production saw world hunger decline in absolute terms and even though some famines did occur between 1970 and 2000 they were much less severe than had been predicted (Butler, 2014). Taking into account the increased food production, famine mitigation and decreased world hunger, in agricultural terms the GR is generally regarded as a successful endeavour (Zimdahl, 2012). Due to the ability of the GR technologies to increase food production, they spread throughout the world including New Zealand (Britney, 2008; Pellegrini & Fernández, 2018).

However, the successes of the GR did not come without some negative consequences. These consequences are varied and include cultural, discrimination, economic, equality, health, political, social, sustainability, and environmental issues (Cleaver, 1972; Jarosz, 2012; Llewellyn, 2018; Pimentel & Pimentel, 1990). The environmental consequences of the GR are linked to many of the other negative consequences however this study will limit its discussion to the direct environmental consequences. Further, even though the GR had negative effects on many aspects of the environment for this study the only negative consequences that will be examined are the use of fertiliser and the leaching of nutrients into waterways.

2.3.2 Consequences of the Green Revolution

The success of the GR was built on new high yielding crop varieties (HYVs) of plants that were able to significantly increase yield per hectare (Evenson & Gollin, 2003). Wheat production for all developing countries increased by 208%, rice by 109%, maize by 157% and potatoes by 78% (FAO, 2004). However, for the HYVs to achieve high yields they required a significantly larger amount of fertiliser than traditional plant varieties and if they did not receive the required high doses of fertiliser their yield was similar, and sometimes inferior, to traditional varieties (Cleaver, 1972; Shiva, 2016). It has been argued that calling the new varieties “high-yielding” is a misnomer because it implies that the varieties are intrinsically high-yielding. However, they are in reality highly responsive to key inputs, including a high application rate of fertiliser. Therefore it has been suggested that the term “high-responsive varieties” replace the term “high-yielding varieties” (Reuter, 2017).

HYVs are designed to consume three to four times as much fertiliser as traditional varieties. Between 1975 and 1990, fertiliser application for grain increased from 15.0 kilograms per hectare (kg/ha) to 75.0 kg/ha (400.0%) in India and the application for rice increased from 25.0 kg/ha to over 150.0 kg/ha (500.0%) in Indonesia (Fitzgerald-Moore & Parai, 1996). On a global level, fertiliser consumption increased by 366.0% between 1961 and 1988. Between 1961 and 2013 N fertiliser consumption increased 759.0% (San Martín, 2017).

From the 1960s the application rate of fertilizer has steadily increased but the efficiency of fertilizer uptake by crops has decreased (Tilman et al., 2002). At current application rates, uptake by crops is approximately 45.0% of applied P fertiliser and only 30.0 – 50.0% of applied N fertiliser (Tilman et al., 2002). Of the remaining nutrients, 7.0% will be taken up by crops in subsequent growing seasons, and the remaining 43.0 – 63.0% will be lost to the surrounding ecosystem (Ladha et al., 2005). The intensification of animal agriculture has resulted in yet more nutrients, in the form of animal excreta, entering the soil-plant system. The combination of excess N and P from fertilisers and animal excreta can leach into ground and surface water and end up in aquatic ecosystems (Carpenter et al., 1998). Fertiliser application can increase the number of microbial groups with functions involved in the processing of N which can result in an increase of N leachate losses by over 400% (Dornbush & von Haden, 2017).

As early into the GR as 1972 the massive eutrophication of lakes, streams and rivers, as a consequence of nutrient leaching and runoff from the heavily fertilised land were being reported (Cleaver, 1972). With the pollution of natural waters from excessively applied fertiliser happening since at least 1972, scientists consider the loss of nutrients from farmland into the environment as a leading socio-ecological problem of the 21st century (San Martín, 2017).

Environmental damage is widely recognised as a threat to the long-term sustainability of the GR's success (Pingali, 2012). It has been noted earlier, with reference to the author Robert Zimdahl (2012) that from an agricultural perspective the GR is generally regarded as a success. However, Zimdahl (2012, p. 199) has a completely different view of the GR when it is looked at from outside a strictly agricultural lens, "The green revolution, while viewed as successful in many quarters, has failed. It has done more environmental damage and brought fewer benefits, especially to poor farmers, than projected".

The environmental damage has also brought into question the success of the GR even from an agricultural perspective despite the increased yields. The HYVs are not high-yielding in and of themselves, the high yields are a function of the availability of agricultural inputs, particularly high rates of fertiliser, which in turn harms the environment (Shiva, 2016). The measurement of GR success, particularly in terms of crop yield, excludes the ecological damage, particularly to the soil, that affects future yields (Shiva, 2016). Shiva contends that the increased yields from the HYVs are insignificant once the increase in inputs and ecological damage that will affect future yields is accounted for. Shiva illustrates this point with a diagram shown in Figure 1. The slowdown in yield growth, first observed in the mid-1980s, can be attributed, at least in part, to the environmental degradation caused by heavy fertiliser use (Pingali, 2012). Data collected from 1961 to 2008 showed that in approximately 40.0% of the areas that grew maize, rice, wheat, and soybean, the annual yields had plateaued or declined (Ray et al., 2012).

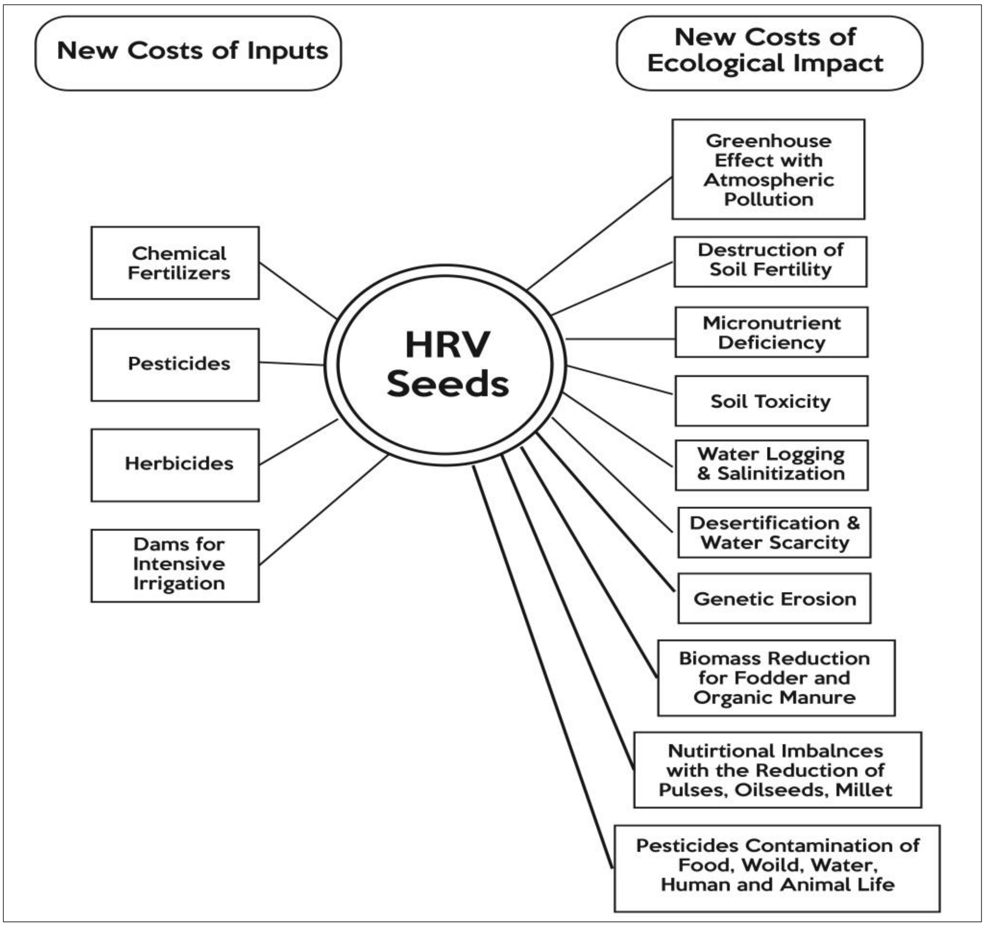


Figure 1: *Ecological cost of the green revolution. Source (Shiva, 1996)*.

It would not be true to say that the impact of the GR on the environment was entirely negative. If the pre-GR global crop yields had not significantly increased, as they did with the GR technology, it has been estimated that by 1999 an additional 1.8 billion hectares of land would have needed to be cleared to equal the GR global harvest. The land clearing would have resulted in the loss of a significant amount of forest, biodiversity and wildlife (Borlaug, 2002).

It is from within the circumstances described above that the technologies, methodologies, benefits, and damage of the GR have entered into, and continue to play a significant role in, mainstream agricultural practice in New Zealand (Wildblood-Crawford, 2006). While the GR has brought the benefits of increased food production, the acceptance of the damage, as described by Shiva (1996), which is done to the life force or mauri of the environment needs to be questioned. The damage caused by GR technologies and advancements presents a significant challenge to Māori landowners as kaitiaki of their land. While embracing GR technologies for their economic prosperity, Māori have a responsibility to do all in their power to protect the environment and restore the depleted mauri to its original strength (Department of Conservation, 1994).

2.4 AOTEAROA-NEW ZEALAND AGRICULTURE

"…New Zealand's growth model is approaching its environmental limits. Greenhouse gas (GHG) emissions are increasing. Pollution of freshwater is spreading over a wider area. And the country's biodiversity is under threat."
-OECD, Environmental Performance Review 2017

2.4.1 Phases of Agricultural Expansion

It has been argued that Aotearoa-New Zealand experienced five major phases of agricultural development between 1840 and 2002, the phases being the colonization phase followed by expansion, early intensification, diversification and later intensification (MacLeod & Moller, 2006). Before the arrival of Europeans in Aotearoa, Māori never used animal manure or any animal by-product as a source of fertiliser, instead wood-ash, decayed vegetable matter, and the fallowing of land was used to promote soil fertility (Polack, 1978; Schaniel, 2001). The use of manure, and later chemical fertiliser, commenced at the colonization phase and continued through the following four agricultural development stages (Best, 1930; Schaniel, 2001; Stewart-Harawira, 2020).

The colonisation phase included the burning of large areas of native vegetation and the introduction and dramatic increase in livestock, particularly sheep. However, sheep numbers began to decline because the grassland soils were quickly depleted of nutrients and the volume of fertilising inputs used was not enough to counteract the depletion (Langer, 1990; Molloy, 1980). The introduction of refrigerated shipping in 1882 commenced the expansion phase by enabling the export of meat and dairy products, not just wool which had been the primary livestock export product, which led to the increased removal of native vegetation and the expansion of grass-based agriculture (Pawson, 2010).

Early intensification was made possible by geopolitical manoeuvring that enabled the exploitation by Aotearoa-New Zealand and Australia of the phosphate reserves on the Pacific Island of Nauru (Gale, 2019). Access to a plentiful and cheap source of phosphate fertiliser saw a 1500.0% increase in application between 1900 and 1925 and was the foundation of a significant increase in production between the 1920s and the 1950s (Hopkins & Wilkins, 2006; Pawson, 2010). Between 1920 and 1970 the availability and use of phosphate fertiliser led to a 150.0% increase in livestock numbers, a doubling of meat and dairy production, and a tripling of wool production which was achieved without needing to increase the area of pasture used for livestock farming (Langer, 1990; Molloy, 1980).

There is conjecture over the commencement date and duration of the diversification phase, however, there was very likely some overlap between the diversification and early intensification phases (MacLeod & Moller, 2006). Diversification began around 1970 and saw a move away from the traditional farming enterprises of sheep, beef and dairy to deer, goats, horticulture and agroforestry (MacLeod & Moller, 2006). The later phase of intensification is generally regarded as having started in the 1980s and continued through to the mid-2000s (Parliamentary Commissioner for the Environment, 2004).

The events surrounding the five agricultural phases, such as the introduction of refrigerated shipping, the use of phosphate fertiliser, and increased livestock numbers, were clearly features of Aotearoa-New Zealand farming. However, there is research that contradicts the early intensification phase moving to a diversification phase, and that the later intensification phase began in the 1980s (MacLeod & Moller, 2006). It is argued that Aotearoa-New Zealand experienced a continuous intensification from the 1960s with a further acceleration of intensification from the early to the mid-1980s, (MacLeod & Moller (2006, p. 212) explain:

> “*We suggest that major expansion of pastoral systems continued until the late 1970s and that intensification has been continuous and has accelerated in*

> *recent times. There has indeed been diversification of agriculture from the 1970s onwards, but this has been added to the national economic benefits from ongoing intensification of the mainstays of agricultural production (dairy, beef and sheep). Diversification did not displace intensification as the dominant trend. Instead, an ongoing trend for intensification overlapped a period of expansion (1960s and 1970s) and a period of diversification (1970s present day)."*

2.4.2 The Aotearoa-New Zealand Gr een Revolution

The adoption of GR technologies in the 1960s supports MacLeod's contention of an ongoing trend of intensification from the 1960s. GR technologies continued the intensification trend that began in the 1920s with the massive increase in the use of P fertiliser that greatly enhanced the expansion and intensification of agriculture.

While Aotearoa-New Zealand did not contribute financially to the CGIAR research institutions it was not a silent observer of the GR developments. Local agricultural scientists obtained HYVs, first from Australia and then directly from CIMMYT in the late 1960s under a collaborative program to test the HYVs in a range of environments throughout the world (Galbreath, 1998). Scientists from the Department of Scientific and Industrial Research (DSIR) conducted their own research program by crossing CIMMYT varieties with a range of other varieties to find the best match for Aotearoa-New Zealand's growing conditions and markets (Galbreath, 1998). This program released the first locally developed HYVs onto the Aotearoa-New Zealand market in 1979 (Galbreath, 1998). Grassland research was a priority for Aotearoa-New Zealand agriculture and became a significant focus of the DSIR (Pawson, 2010). Native grass species were quickly replaced with English grasses which initially grew well but began to decline after a few years. A number of locally researched scientific developments resulted in a grasslands revolution in Aotearoa-New Zealand. Of all the developments none was more important than the application of P fertiliser which ultimately enabled the intensification of animal-based agriculture (Galbreath, 1998).

The GR farming model that was adopted by Aotearoa-New Zealand is based on maximised productivity at the expense of all other considerations including the environment (Davis et al., 2019; Pimentel & Pimentel, 1990). This is evident from the government and the agrichemical industry's response to the human health and environmental problems that began to be identified in the 1950s. Although the government made legislative changes to the Food and Drug Regulations Act and the Agricultural Chemicals Act in response to the findings, the use of agrichemicals, including fertiliser, continued to increase with the guidance and encouragement of government and industry (Galbreath, 1998; Pawson, 2010; Wildblood-Crawford, 2006). The response of industry to the 1962 publication of Silent Spring (Carson, 2009), which invigorated public discourse on how agrichemicals could compromise human health and the environment, was a sustained campaign promoting not just the necessity but the morality and value of agrichemical use (Wildblood-Crawford, 2006). Despite any misgivings about possible environmental issues, Aotearoa-New Zealand followed a similar path to other countries that adopted GR technologies with a large and steady increase in fertiliser use from 1960 (Liu et al., 2015).

2.4.3 Fertiliser Use in Aotearoa-New Zealand

Regardless of the beginning, ending or overlapping of agricultural phases, features and events, it is clear that the increased use of N and P fertiliser played a significant role in the expansion, intensification and increased productivity of agriculture in Aotearoa-New Zealand.

FAOSTAT records the total consumption of N fertiliser in 1961 as 4,264 tonnes and 40,000 tonnes in 1984 before a large decrease to 22,200 tonnes in 1989. A large increase in consumption took place between 1990 and 2002 with 45,800 tonnes in 1990 which was more than double the previous year and almost 11 times the amount of 1961. Figure 2 provides data on the consumption of nitrogenous fertilisers from 1961 to 1990.

The years from 1991 to 2019 generally saw an annual increase, which occasional slight declines, in the amount of N applied to soil in fertiliser. The time from 1991 to 1996 saw steady increases before a drop of 11,000 tonnes, to 143,000, in 1997. 1998 application increased by 12,000 tonnes to 155,000 and grew to 355,000 tonnes in 2005 before experiencing a drop of 45,000 tonnes the following year.

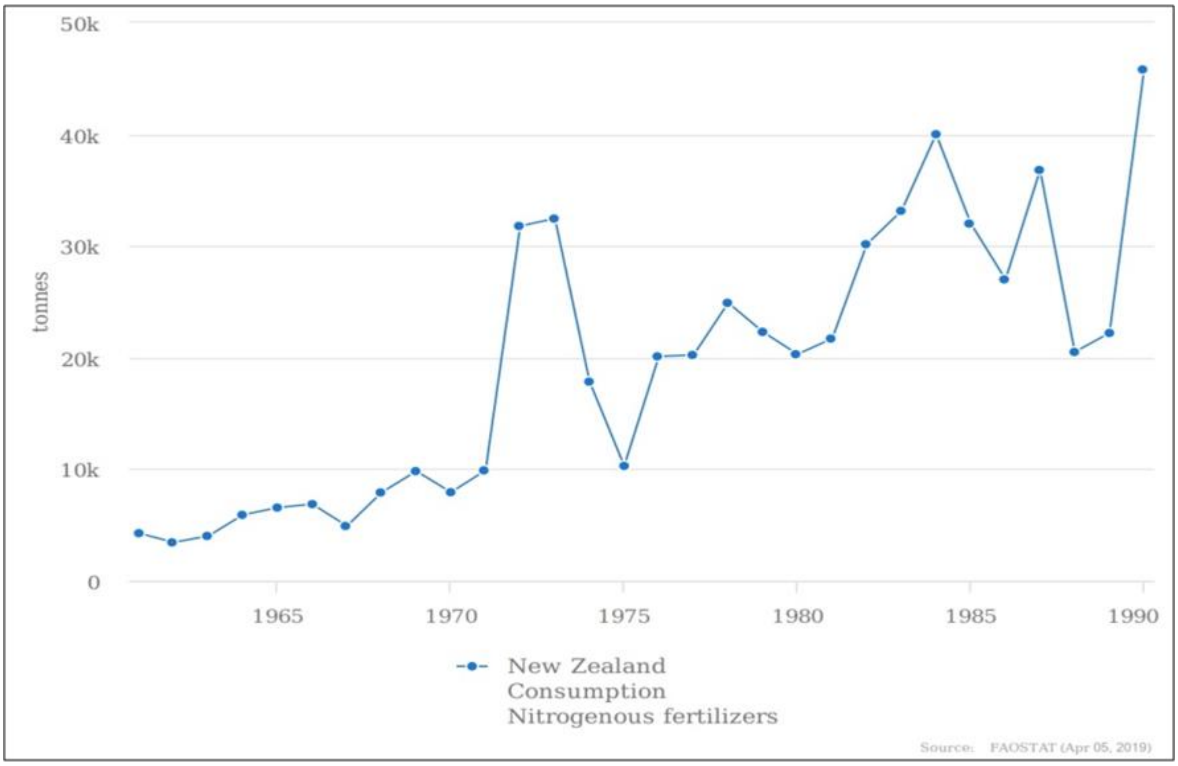


Figure 2: *Consumption of nitrogenous fertilisers in Aotearoa-New Zealand from 1961 to 1990. Source (FAO, 1997)*

The years 2007 and 2008 saw increases in the application before a decrease of 31,000 tonnes in 2009 to 297,000. An increase of 44,000 tonnes occurred in 2010. By 2019 the number of tonnes had increased to 452,000 which equates to an increase in the application of N fertiliser of 629.0%. Figure 3 provides data on the tonnes of N applied in fertiliser to farmland in Aotearoa-New Zealand from 1991 to 2019.

After gaining access to the Nauru phosphate in the 1920s, Aotearoa-New Zealand was consuming a large amount of phosphate fertiliser (Pawson, 2010). According to FAOSTAT the total use of phosphate fertiliser in 1961 was 204,948 tonnes which is almost 50 times the amount of N fertiliser for the same year. The following 28 years, up to 1990 saw a mixture of increasing and decreasing use with a high of 446,200 tonnes in 1973 and a low of 178,500 tonnes in 1988. Use in 1990 was 214,200 which was only 4.5% higher than the 1961 rate. Figure 4 provides data on the consumption of phosphate fertiliser in Aotearoa-New Zealand between 1961 and 1990.

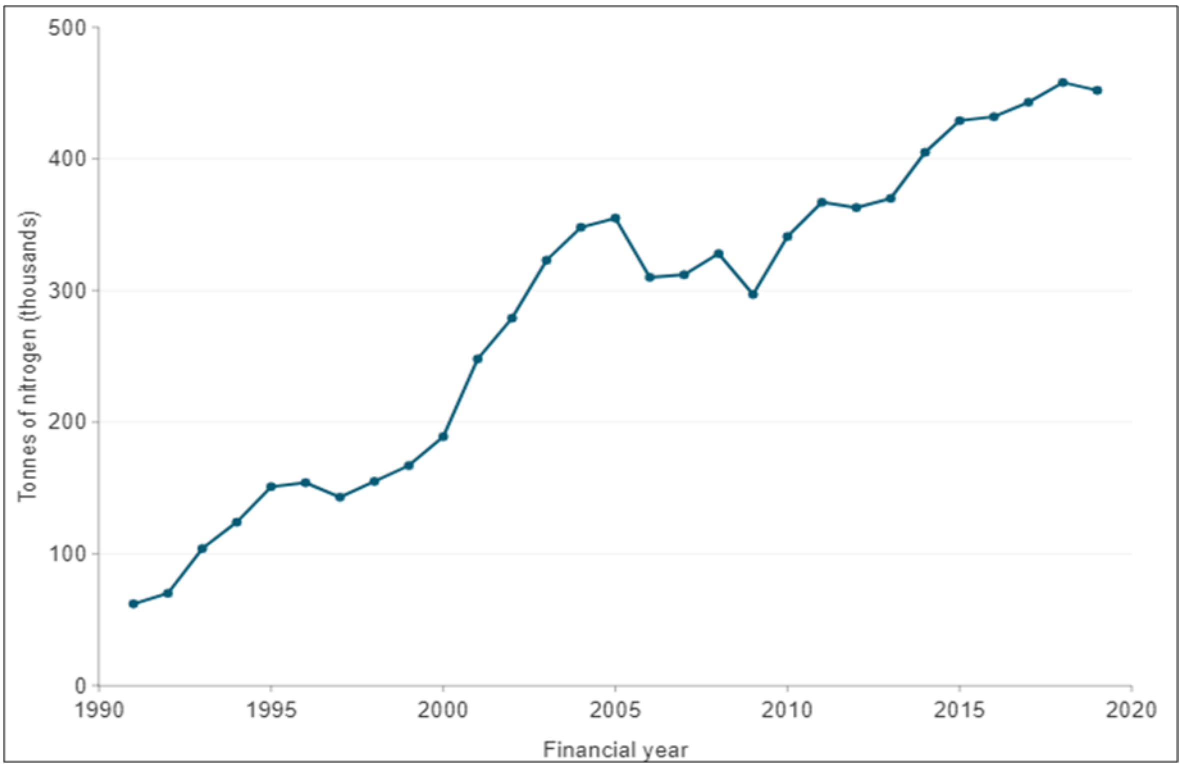


Figure 3: *Tonnes of N applied in fertiliser in Aotearoa-New Zealand from 1991 to 2019. Source (Stats NZ, 2019a)*

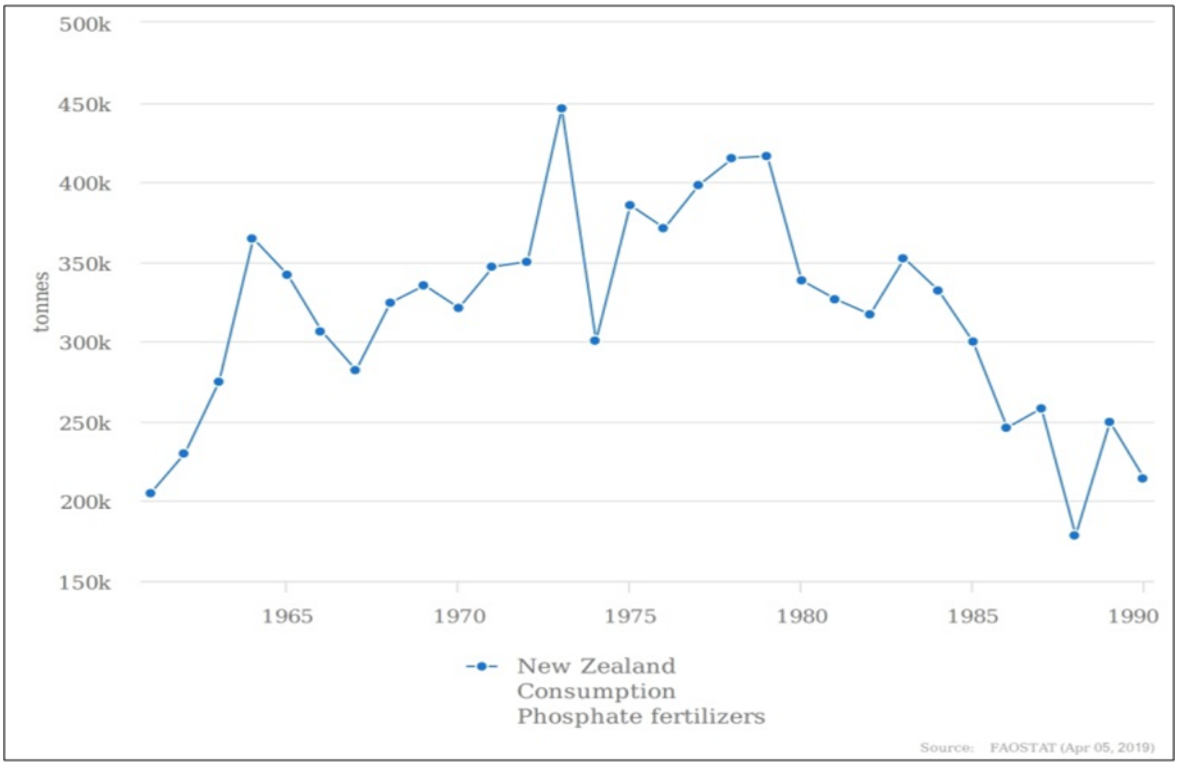


Figure 4: *Consumption of phosphate fertilisers in Aotearoa-New Zealand from 1981 to 1990. Source (FAO, 1997)*

Phosphorus applied to soil in fertiliser, for the period 1991 to 1996, saw a sharp increase from 94,000 tonnes to 171,000 tonnes before a slight decrease for the period

1997 to 1999. The year 2000 saw an increase of 10,000 tonnes to 177,000 before 4 years wherein all except for 1 year an increase was experienced. Phosphorus applied in fertiliser peaked in 2005 at 219,000 tonnes and for the next 4 years saw an annual decrease before an annual increase for the years 2010 to 2012. The next 7 years saw decreases and raises with the largest annual decrease being 16,000 tonnes in 2013 and the largest increase being 23,000 tonnes in 2014. Figure 5 provides data on the amount of P in fertiliser that was applied to farmland in Aotearoa-New Zealand from 1991 to 2019.

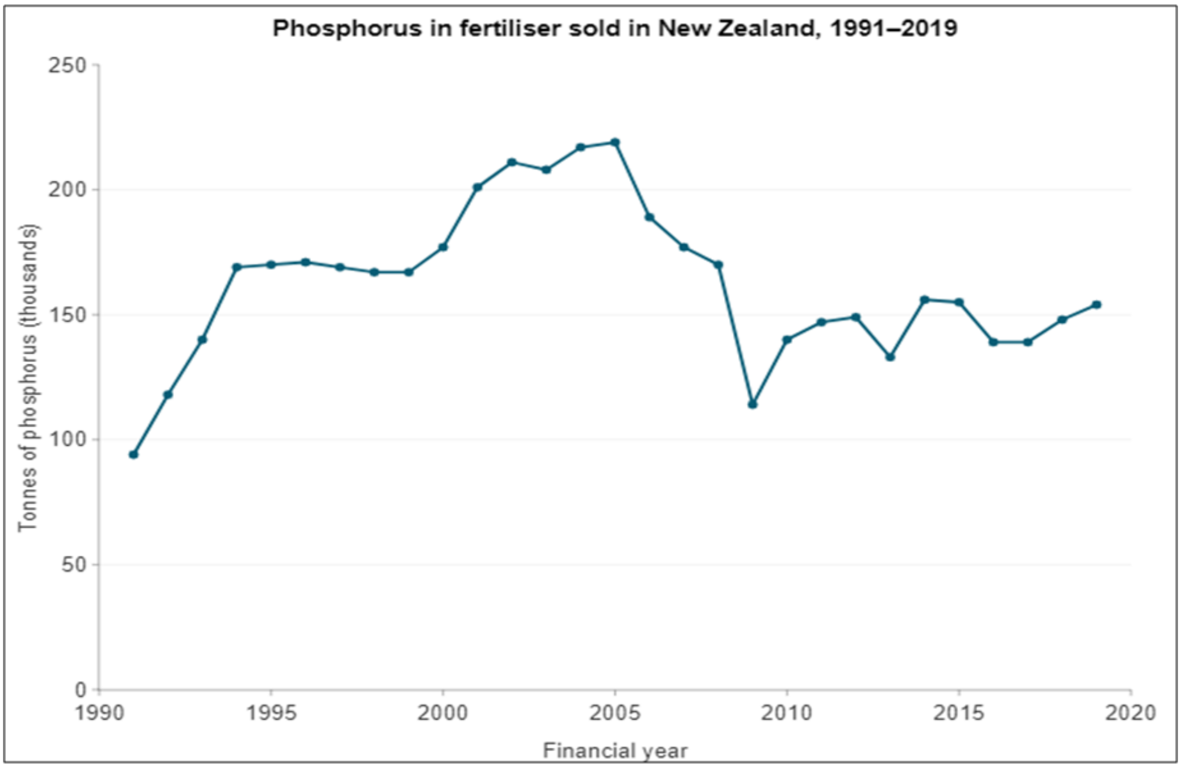


Figure 5: *Tonnes of P applied in fertiliser in Aotearoa-New Zealand from 1991 to 2019. Source (Stats NZ, 2019b)*

2.4.4 Nitrogen and Phosphorus per Hectare

The total amount of fertiliser used in Aotearoa-New Zealand is a secondary factor concerning the fertiliser volumes as it relates to N and P leaching. Nutrient leaching is driven by several factors including land-use type, soil management, farming practices, climatic conditions and soil properties (Lehmann & Schroth, 2003). However, the main cause of N and P leaching is the application of fertiliser in a volume that exceeds the crops' demand for, or ability to, uptake the volume of applied nutrients (Liu et al., 2019; Wang & Li, 2019). Taking the main cause of N and P leaching into account, the most important factor concerning the volume of fertiliser is its application rate per area of land.

While N and P fertiliser use increased from 1961 to 2015, the amount of agricultural land where the fertiliser was applied decreased by 32.0%, or from 16.05 million to 10.8 million hectares, over the same period. Therefore, the increase in the volume of N and P used, and its impact on leaching is exacerbated by the increased volume of fertiliser being applied to a smaller area of land. Figure 6 provides data on the amount of agricultural land in Aotearoa-New Zealand from 1961 to 2015.

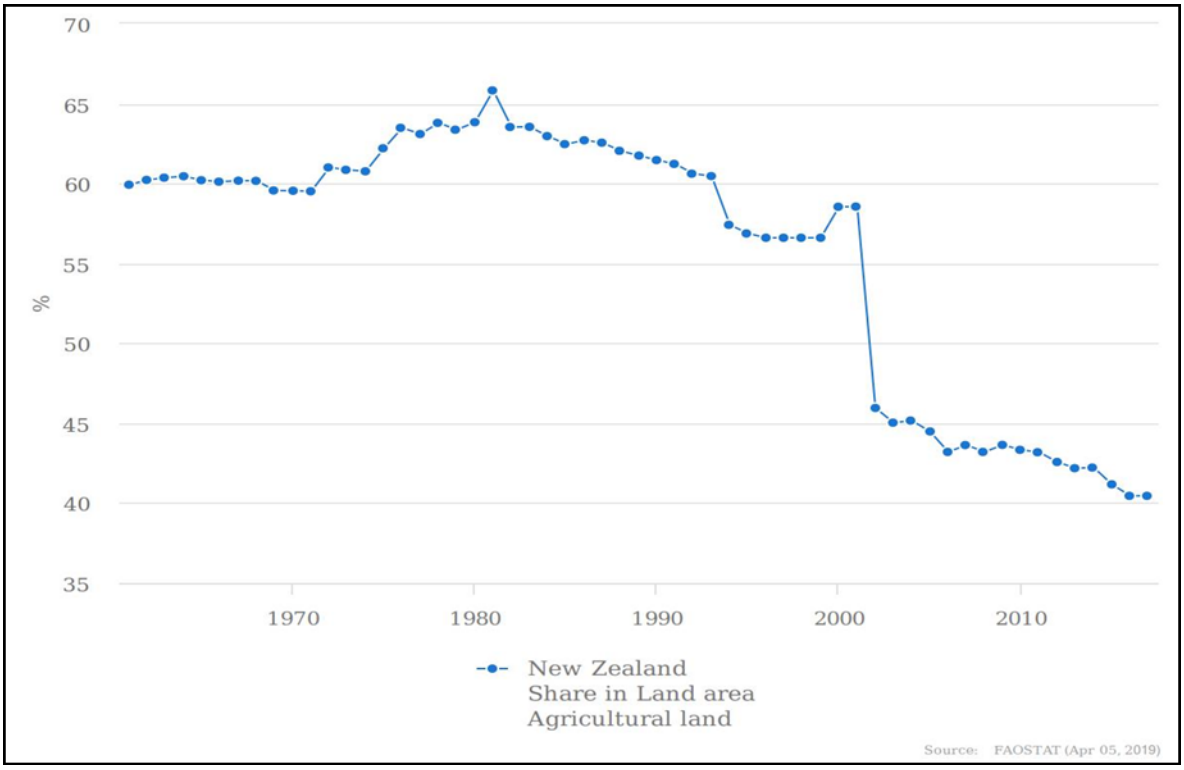


Figure 6: *Agricultural land as a % of Aotearoa-New Zealand's land area from 1961 to 2015. Source (FAO, 2019)*

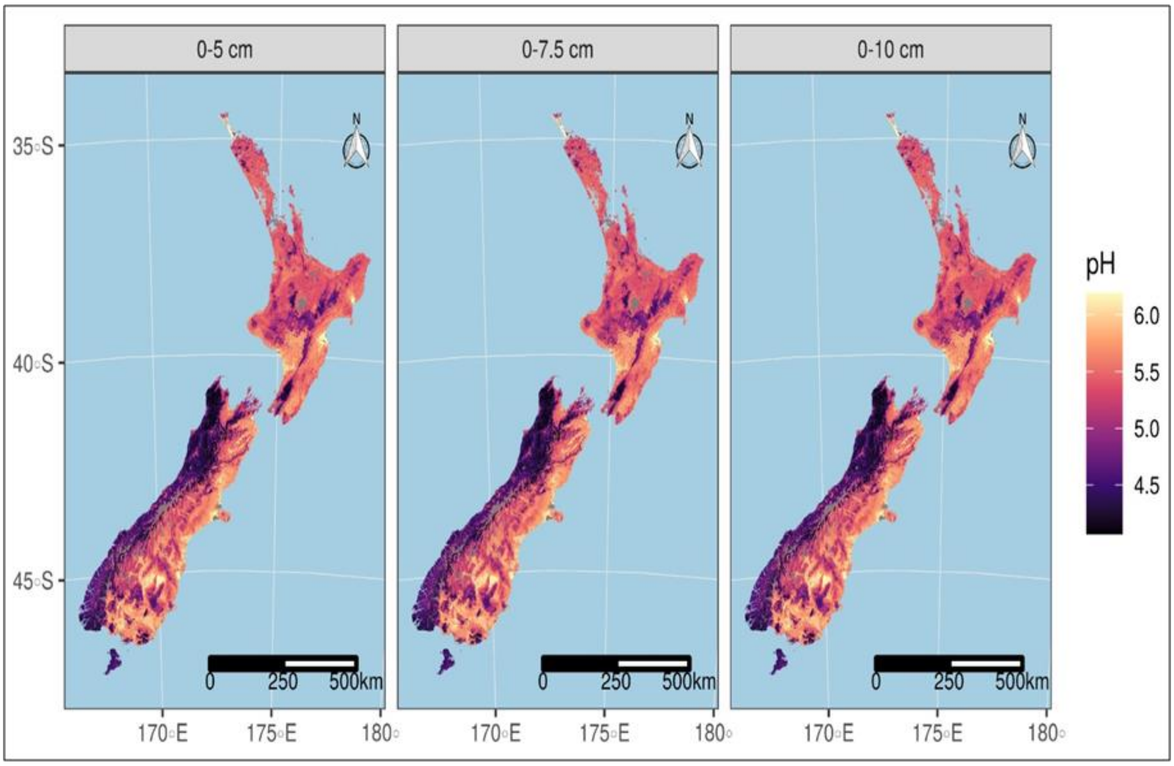
Between the years 2002 and 2016, total fertiliser use per hectare of arable land in Aotearoa-New Zealand reached its peak in 2005 at 2,719.0 kg/ha and its low in 2010 at 1,271 kg/ha. In 2011 fertiliser consumption increased by 510.0 kg/ha to 7,781.0 kg/ha before experiencing 3 years of slight decline followed by 2 years of increase up to 1,777.0 kg/ha in 2016. As of 2016 Aotearoa-New Zealand was the world's 4th largest consumer of fertiliser per hectare of arable land (World Bank, 2019).

Between 1996 and 2002, N fertiliser use increased 162.0% on Aotearoa-New Zealand dairy farms (MacLeod & Moller, 2006). By 2017 dairy farming was the highest user of N fertiliser at 63.0% of Aotearoa-New Zealand's total use, and the second-highest user of P fertiliser (Stats NZ, 2016). Before the 2000s, dairy farms relied predominantly on N2 fixation as their source of N input and the average application of N by fertiliser was only 40.0 kg/N/ha (Ledgard et al., 1999). N use had increased to 115.0 kg/N/ha by 2005 (Clark et al., 2007), before experiencing a slight drop to 114.0 kg/N/ha in 2007 (Basset-Mens et al., 2009). By 2015-2016 the average use of N as applied by fertiliser for Aotearoa-New Zealand dairy farms was 126.0 kg/N/ha (Pinxterhuis, 2019).

Phosphorus application has followed a similar increasing trend to that of N. The national average of P applied as fertiliser to intensive dairy farms was 28.0 kg/P/ha in 2001-02 (Parfitt et al., 2008). By 2007 the national average for dairy farms had almost doubled to 49.0 kg/P/ha (Basset-Mens et al., 2009). The view of the increased application of P by fertiliser is supported by Waikato Regional Council data that shows excess P in soil samples from half the monitored dairy farms in 2012 compared to about one-fifth between 1998 and 1996 (Waikato Regional Council, 2018). When taking into account that the total amount of P applied as fertiliser increased by 36.0% between 2009 and 2015 and the total area of agricultural land began steadily decreasing from the year 2000 it is clear that the national average of kg/P/ha increased as did N.

2.4.5 Acidic Soil and Lime Use in Aotearoa-New Zealand

The natural geological and environmental conditions of Aotearoa-New Zealand, particularly the country's vast forest coverage, led to its soil being predominantly acidic and naturally low in nutrients (Hewitt et al., 2021; Parliamentary Commissioner for the Environment, 2004.). Aotearoa-New Zealand soil's natural state of acidity has undergone further acidification as a result of standard farming practices, particularly the use of N fertilisers (Anderson et al., 2013). Over 50.0% of the world's potentially arable land is acidic and it is a widespread problem in Aotearoa-New Zealand (Morton, 2020; Zheng, 2010). The extent of the problem has been demonstrated visually with the 3D mapping of Aotearoa-New Zealand's soil pH (Roudier et al., 2020). A map showing the predicted soil pH of Aotearoa-New Zealand's soil landscape is provided in Map 1.



Map 1: *Soil pH of Aotearoa-New Zealand's landscape. Source (Roudier et al., 2020)*

Problems arise due to a change in the soil's chemical and biological properties when acidity reaches a pH of 5.5 or lower. When the pH drops below 5.5 the largely insoluble and chemically immobile aluminosilicates and aluminium-hydroxide minerals become a soluble and chemically mobile form of aluminium (Anderson et al., 2013; Silva, 2012). Soluble aluminium (Al) is toxic to plants and can hinder their growth and development by inhibiting root formation, thereby affecting the plant's ability to uptake water and nutrients, and affecting the growth and integrity of the plant's central tissue (Silva, 2012; Zheng, 2010). Although Al toxicity is recognized as the primary limiting factor of crop and pasture yield associated with acidic soils (Venter, 2017), the fact that clay minerals, which are rich in acid soils, can fix P and make it unavailable for plant uptake is also a significant problem (Zheng, 2010).

Applying lime to agricultural land in Aotearoa-New Zealand began sometime between the late 1800s and early 1900s (Edmeades et al., 1984). Since this time, liming has become a common farming practice and is the principal method used by farmers to reduce soil acidity. According to the Ministry for the Environment (2021), the historical consumption of lime followed a similar trend to that of N and P fertilisers which both experienced a rapid increase in consumption from 1990 before experiencing a general decline between 2001 and 2016. Consumption of Lime in 1990 was 800,000 tonnes and increased to Aotearoa-New Zealand's consumption peak of almost 1.8 million tonnes in 2002. Between 2002 and 2016 there was a general decline in consumption that was interspersed with occasional increases. Also like N and P, lime experienced its most rapid increase during the time that the land area used for agriculture declined. Figure 7 provides data on lime usage in Aotearoa-New Zealand from 1990 to 2019.

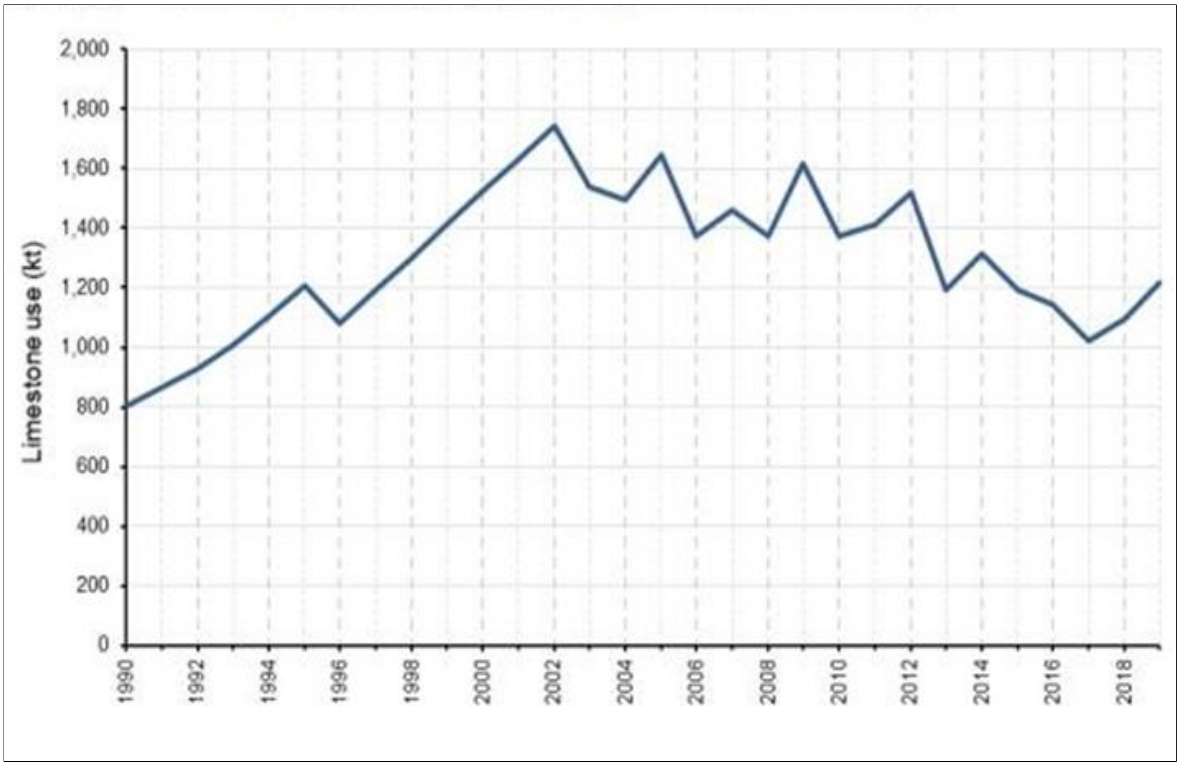


Figure 7: *Limestone usage on agricultural land in Aotearoa-New Zealand from 1990 to 2019: Source (Ministry for the Environment, 2021)*

The application of lime is the most effective strategy to ameliorate soil acidity (Moir & Morton, 2018). Lime, which is an alkaline material, can neutralise the acid, or hydrogen ions, in the soil which reduces soil acidity and raises soil pH (Li et al., 2019).

The application of lime to farmland is generally promoted as being environmentally benign or beneficial (Parliamentary Commissioner for the

Environment, 2004). However, significant environmental problems can arise including an increase in greenhouse gas emissions (Carran, 1992; Mkhabela et al., 2006), and an intensification of the leaching of several nutrients including N (Haynes, 1982; Røsberg et al., 2006).

While acknowledging potential productivity problems associated with the overuse of lime, its application to farmland is promoted as an essential practice if optimal production rates, and economic outcomes, are to be achieved (Sime, 2001). However, the use of lime can reduce productivity in several ways, some of which are difficult for a farmer to recognize and quantify. Although lime is capable of reducing P leaching under some circumstances (Murphy & Stevens, 2010; Ulén & Etana, 2014), it can also, under some circumstances, transfer plant-available P into an unavailable form which can result in a P deficiency that inhibits crop and animal production (Goff, 2009; Grant et al., 2001; Matichenkov et al., 2002).

Lime is not always effective at combatting soil acidity within the rhizosphere. Changes made to the rhizosphere by the plant roots can result in pH changes in the rhizosphere of up to 1 – 2 pH units (Hinsinger et al., 2006). Despite the presence of lime in the soil, acidity can increase due to the plant's root exudation and respiration which will result in a build-up of CO2 which in turn will form carbonic acid in the rhizosphere. Except for soil that is already highly acidic, this exudation and respiration process will result in an increase in acidity (Hinsinger et al., 2003). In order to maintain the balance of anions and cations in the soil, plant roots can increase the concentration of protons which in turn promotes the secretion of acids that are strong enough to dissolve a range of soil minerals. The root induced changes in the acidity of the rhizosphere not only increase the bioavailability of many nutrients but also of toxic metals including Al (Hinsinger et al., 2006).

2.4.6 Clean-Green Aotearoa-New Zealand

The wholehearted adoption of GR technologies has seen significant agricultural advancements in Aotearoa-New Zealand. The primary industry sector dominates Aotearoa-New Zealand’s merchandise exports and accounts for over 70.0% of export value and an overall contribution of 7.0% of the country’s Gross Domestic Product

(GDP) (World Trade Organization, 2015; Stats NZ, 2020). Agriculture is the most productive industry group within the primary industry sector and contributed 65.0% of the primary industry's contribution to the GDP in 2020 and was the 11th most productive industry overall (Stats NZ, 2020).

The success and productivity of Aotearoa-New Zealand’s agricultural industry have come at a price not only to other industries but potentially to itself. The agricultural industry is primarily an export industry with 85 – 90.0% of its products being exported (International Trade Administration, 2021). In 1999 the ‘100% Pure’ marketing strategy commenced with the intent of showing the world that Aotearoa-New Zealand is a premium tourist destination. Since its launch the 100% Pure campaign has expanded its marketing influence to Aotearoa-New Zealand’s agricultural products and words such as ‘healthy’, ‘clean’, ‘green’, ‘trusted’, and ‘safe’ are so strongly associated with the country’s products that Aotearoa-New Zealand’s tourism brand and agricultural exports have become inextricably linked (OECD, 2017; Steele, 2016). The 100% Pure brand is built on the perception of a pristine environment that includes fresh and clean water, but this perception is being challenged and the stark difference between the perception and reality of Aotearoa-New Zealand’s environment is being exposed (Joy, 2011; OECD, 2017; Steele, 2016).

The clean-green image of Aotearoa-New Zealand is said to be worth hundreds of millions, and possibly billions of dollars per annum in the export of goods and services and tourism (Ministry for the Environment, 2001). Aotearoa-New Zealand’s key export customers have indicated that the clean-green image of its products has a significant export value. The image and perception is a key driver in the value of goods and services in international markets and creates a high level of expectation from tourists (Ministry for the Environment, 2001a).

If Aotearoa-New Zealand’s environment was perceived as being degraded then key export customers, on average, would purchase 54.0% fewer products. Tourism would also be similarly devastated with Australian, Japanese, and Korean tourist stays reducing by 48, 79, and 77.0% respectively (Ministry for the Environment, 2001a).

The Māori economy is valued at $68.7 billion with assets largely concentrated in the primary industries with some diversification to other areas including hospitality and tourism (Nana et al., 2021). 7.0% of the Māori workforce is employed in the primary industries and 17.0% are employed in hospitality and tourism (Nana et al., 2021). If the clean-green reputation and image of Aotearoa-New Zealand is damaged the Māori economy and individual Māori employment could suffer a tremendous loss. The reduction of nutrient leaching from farmland and an increase in water quality can help protect Māori prosperity and well-being at a general level. It is incumbent on Māori as kaitiaki of their land to do all in their power, not only to protect and restore the mauri of the environment, but to also protect the mauri of all the offspring of Papatūānuku, Māori and non-Māori alike.

2.5 MĀORI AGRICULTURE

"E tipu e rea, mō ngā ra ō tōu ao. Ko tō ringa ki ngā rākau ā te Pākehā hei ara mō tō tinana. Ko tō ngākau ki ngā taonga ā ō tīpuna Māori hei tikitiki mō tō mahuna. Ko tō wairua ki tō Atua, nāna nei ngā mea katoa."

Grow up and thrive for the days destined to you. Your hands to the tools of the Pākehā to provide physical sustenance. Your heart to the treasures of your Māori ancestors as a diadem for your brow. Your soul to your God, to whom all things belong.

- Sir Apirana Ngata

2.5.1 Introduction

The Māori Agriculture section of the literature review will describe early Māori horticultural practices and the successful transition from horticulture into agriculture. Many of the factors that led to Māori's rapid rise and domination of the agricultural sector in Aotearoa-New Zealand will be identified, including:

1. The unique hybrid cultivation system
2. The application of long-established kaitiakitanga practices
3. Continual innovation, ingenuity, and adaptability
4. High business acumen

The review will identify some of the reasons for the decline and eventual collapse of post-treaty Māori agriculture. Of particular importance to this study is the identification of aspects of the agricultural system and kaitiakitanga practices, which were so important to the success of Māori agriculture, that were abandoned or were made impossible to implement on a large scale due to colonisation and land confiscation. The review identifies the enormous problems faced by Māori concerning agriculture, from the arrival of their Polynesian ancestors in Aotearoa to the challenges faced in modern times, and how they were able to adapt, implement new ways of doing, and at least partially overcome these problems. These events are important because Māori are again facing a significant problem with the leaching of nutrients from their farmland into natural waters. The nutrient leaching problem will require a similar response to that of the problems faced by previous generations of Māori with the adaptation of practices and the adoption of new ways of doing. The full extent of the problems encountered by early Māori and how they not only overcame the problems but also prospered from their response is directly relevant to contemporary Māori and this study.

The early Māori agricultural experience was not a “one-size-fits-all” experience. Some individuals and groups of Māori experienced tremendous success and others experienced tremendous failure. Some Māori demonstrated a vast amount of ingenuity and adaptability while others could not or would not step outside standard approaches and practices. Many Māori demonstrated a keen understanding of commerce, economics, and were consummate capitalists, while others struggled with the concept of investing in new technology. Even issues of tikanga Māori, as they related to agriculture and commerce, were dealt with differently by different tribes, hapū, whānau and individuals, and not even something as tapu as the use of animal by-products was universally followed. Nothing in this review should be understood as representing the entirety of Māori experience or thought.

A final caveat concerns pre-1876 agricultural statistics. While pre-1876 statistics are used in this literature review and in many works authored by researchers of early Māori agriculture, these statistics should be considered broad generalisations only. Hargreaves (1960, pg. 2) states that some of the Pre-1876 data were not only defective but in some cases so “manifestly erroneous” that it is “not worthy of publication.” The caveat employed by Hargreaves (1960) is also employed by this work, in that the statistical data and maps of pre-1876 Māori agriculture should only be viewed as approximate data and nothing more than a generalised picture.

2.5.2 Defining Agriculture

The practice of horticulture, while having many overlapping and related features, is a different practice from that of agriculture. Even though a difference between the two is almost universally accepted, the definition of each and the boundaries between the two are far from settled (Adams, 2012). One of the commonly used distinctions between horticulture and agriculture is that horticulture is gardening and is the practice of growing plants whereas agriculture is farming that relies on large machinery and takes place over a large area of land. However, as Adams (2012) points out, this definition works when vegetables and fruit are grown on a small scale, but it does not clearly characterise all situations such as large-scale production of gardening goods. Another commonly used distinction between the two practices is that horticulture deals exclusively with the growing of plants, including trees, vegetables, fruits, and flowers, not only for food but also for medicine and decoration. Alternatively, agriculture is the practice of the large-scale cultivation of food crops and raising livestock and poultry to sell and generate a monetary profit (Hatfield et al., 2014).

For the purposes of this study and the proceeding discussion on Māori horticulture and agriculture a simple definition with clearly set boundaries between the two will be used. Māori horticulture is defined as the practice of growing plants primarily for local use and limited trade. Māori agriculture is defined as the practice of growing plants and raising livestock for the purpose of producing food for self and for trading and selling for profit.

The indigenous settlers of Aotearoa were Polynesian voyagers who arrived on its shores sometime in the mid to late 1200s and evolved into the Māori, a unique indigenous culture (King, 2019). The Polynesian ancestors of the Māori arrived with long-established practices for the growing of food crops and there is significant evidence from the archaeological record that these growing practices were adapted to fit local circumstances and environmental conditions (Furey, 2006). Ecological and environmental knowledge, ranging from food sources, harvesting practices, marine and freshwater resource management, was also adapted to fit local circumstances (Whaanga et al., 2018). A substantial body of work was produced by early Māori detailing and codifying this knowledge via oral tradition that included the mediums of whakataukī (proverbs), maramataka (lunar calendars), karakia (incantations), pūrākau (narratives), and waiata (songs and chants) (Whaanga et al., 2018).

Pre-European Māori were horticulturalists who also obtained meat, wild and semi-domesticated plants, seafood, and freshwater food from "hunter-gatherer" activities (Cambie & Ferguson, 2003). Pre-European Māori engaged in limited animal husbandry with the raising of Kuri dogs (*Canis familiaris*) and birds such as the black-back gull (*Larus dominicanus*) (Challis, 1995; Hargreaves, 1963; Hutching, 2006; Woods, 2014). However, it was not until the introduction of European livestock, non-traditional crops, and cultivation tools that Māori become agriculturalists that raised livestock and grew and collected food for the purpose of commerce.

As agriculturalists, Māori used a hybrid system of farming that allowed the use of traditional horticultural and food gathering practices combined with European practices and tools. This hybridity allowed for large-scale commodities trading while continuing to meet the food requirements for local Māori (Pool, 2015a). Hybridity enabled Māori to adopt a "best of both worlds" approach which proved to be more productive than an "either-or" approach. The "best" approach used by Māori included the total rejection of some European practices on tikanga Māori grounds, particularly tapu, such as the use of manure and other animal by-products to fertilise the soil, while simultaneously adopting the use of European iron tools. Other "best" practice approaches included continuing to plant some crops in the traditional clumping formation as opposed to the European method of planting in rows.

The hybrid system ensured that tikanga Māori could be observed and that the ecosystem could be protected and restored through the application of traditional kaitiakitanga practices. The use of silicon-rich substances, as a practical tool in traditional Māori kaitiakitanga practice, will be discussed in the proceeding paragraphs, particularly its co-dependant role with the practice of rāhui in restoring the mauri of exhausted soils by re-establishing soil fertility, microbiological diversity, and the soil's physical and chemical properties.

2.5.3 Māori Horticulture

Tahitian navigator Tupaea (Tupaia, Tupa'ia), who was accompanying James Cook and the crew of the Endeavour on its first exploration of the South Pacific, arrived in Aotearoa in 1769 (Salmond, 2012; Tapsell, 2009). Upon arriving at Tūranganui-a-Kiwa on the East Coast of Aotearoa, the Endeavours botanist, Joseph Banks, inspected Māori horticultural plots at Anaura Bay (Horrocks et al., 2008). Recorded in the journal of banks in the spring of 1769 is the following description of the horticultural system and infrastructure he saw:

> *"...so well was the ground tilled that I have seldom seen...land better broke down. In them were planted sweet potatoes, cocos [yams], and some of the cucumber kind [taro]...; the first of these were planted in small hills, some ranged in rows others in quincunx, all lad by a line most regularly, the cocos were planted in flat land..., the cucumbers were set in small hallows or dishes, much as we do in England. These plantations were from 1 or 2 to 8 or 10 acres each, in the bay might be 150 or 200 acres in cultivation...Each distinct patch was fenced in, generally with reeds placed close one by another, so that scarce a mouse could creep through". (Horrocks et al., 2008, p. 1).*

Centuries before the arrival of Tupaea, the Polynesian ancestors of the Māori of Aotearoa had populated the Pacific and intentionally introduced approximately 70 species of plants. These plants were a combination of tropical Asian-Pacific and American species, and growing practices for those plants were adapted to the different conditions of each settled area (Horrocks et al., 2008). Of these 70 introduced species up to 12 have been identified as being introduced to Aotearoa but this number is considered the minimum as other species could have disappeared before European arrival due to the temperate climate (Horrocks et al., 2008). The ability of the original Polynesian settlers of Aotearoa to adapt tropical climate growing practices to a temperate climate can be considered one of the early settler's greatest accomplishments and testifies of their high level of horticultural skill (Horrocks et al., 2008; Roskruge, 2009).

The growing practices employed by Māori were meticulous, effective, and demonstrated a thorough understanding of soil and crop cultivation. For example, the cultivation of kūmara started with the propagation of the plant because no variety was able to flower in Aotearoa (Roskruge, 2009). Soil preparation was intricate and intensive and included the clearing of existing vegetation, often by burning, and the removal of roots, stumps, and rocks from the cultivation site (Burtenshaw, 2010). While stones and rocks would be removed from cultivation sites they were also systematically added to the soil in order to absorb heat and increase soil moisture retention (Burtenshaw, 2010). Improved soil drainage and aeration were achieved by adding gravel, sand, or crushed seashells (Gumbley & East, 2013). Grass (*A. toetoe, A. fulvida, A. splendens, A. richardii, A. turbaria*) could also be added to the soil for mulching purposes and kānuka (*kunzea ericoides*), mānuka (*Leptospermum scoparium*), and other timbers were deliberately burnt to add wood ash and charcoal to the soil (Burtenshaw, 2010; Roskruge, 2011). In some areas, Māori would create compost by mixing wood ash, with leaf and branch matter which was added to the soil (Roskruge, 2011). The fertilising strategies of Māori were purposeful and intensive and resulted in the creation of charcoal-laden topsoil which analyses have shown to have produced elevated levels of N, P and potassium (Roskruge, 2011). The addition of wood ash was described by Hargreaves (1963, p. 102) as a purposeful act with the specific intention of fertilising the soil:

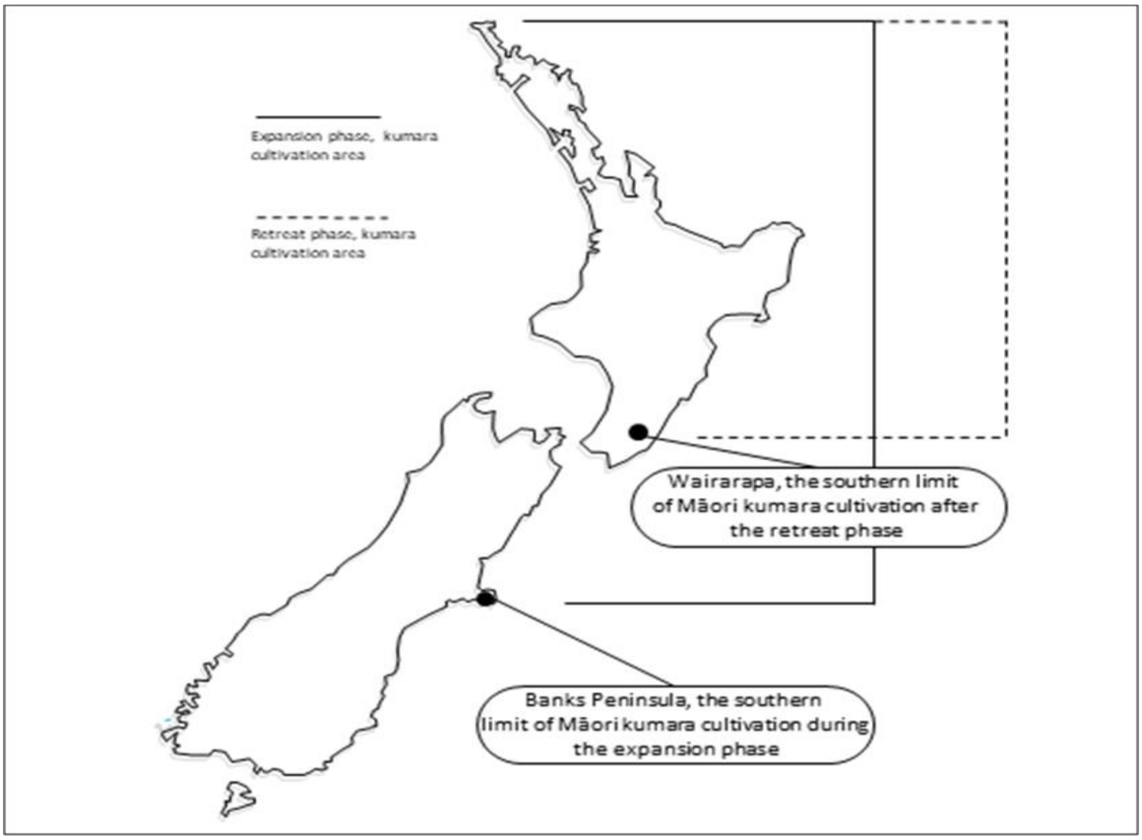
> *"The one fertiliser easily obtainable by the classical Māori agricultural was wood ash, and he fully understood the importance of its application to his soils. All wood, brush, and fern burnt during clearing operations provided ash which was carefully collected and spread over the land to be planted."*

Kūmara was grown in soil that was formed into mounds, other crops were grown in concave bowls, rows, and beds, around which wind-break fencing was erected around flat, terraced, or sloped plots (Burtenshaw, 2010; Furey, 2006). Māori growing plots were generally free of weeds due in large part to the practice of fallowing land and meticulous weed extraction (Leach, 2005). A joint project between Nga Mana Toopu o Kirikiriroa and the Hamilton City Council has seen the establishment of Aotearoa-New Zealand's only traditional Māori garden. The garden, named Te Parapara Garden, was constructed at the Hamilton Gardens and was designed to replicate a traditional cultivation site (Hamilton Gardens, 2021). A picture of the garden is shown in Figure 8.

Figure 8: *Te Parapara kūmara cultivation garden: Source: Authors private photo, 2021.*

The growing practices used by Māori were not those practised in Polynesia and they were not adopted by accident. Using the changing cultivation techniques for kūmara as an example, there is a clear process of growing practice development. Similar in structure and function, if not in number, to the five phases of agricultural development in New Zealand posited by MacLeod & Moller (2006), Kūmara growing went through a three-stage development process. First, a wide variety of kūmara cultivars and growing practices were introduced to Aotearoa by Polynesian settlers. The second was a phase of experimentation and selection, whereby the best practices and most successful cultivars were developed. The third stage was the expansion of the growing practices and kūmara cultivars to different growing areas and regions (Burtenshaw, 2010; Yen, 1963).

Expansion saw the kūmara being grown from Northland to as far south as the Banks Peninsula (Anderson, 2016). The geographical locations where kūmara was grown in Aotearoa would later shrink and retreat northward during the period between 1450 and 1650. The retreat saw cultivation sites as far south as the Banks Peninsula, as far west as the Marlborough Sounds, and as far north as Wairarapa being abandoned (Burtenshaw, 2010). Several reasons for the retreat have been put forward, including climate change, demographic changes, excessive rainfall, cyclonic events, prolonged dry spells, forest clearance, earthquakes, and tsunami (Anderson, 2016; Furey, 2006). Map 2 illustrates the geographical areas, outlined by Burtenshaw (2010) and Anderson (2016) where kūmara was generally grown during the expansion and retreat phases.

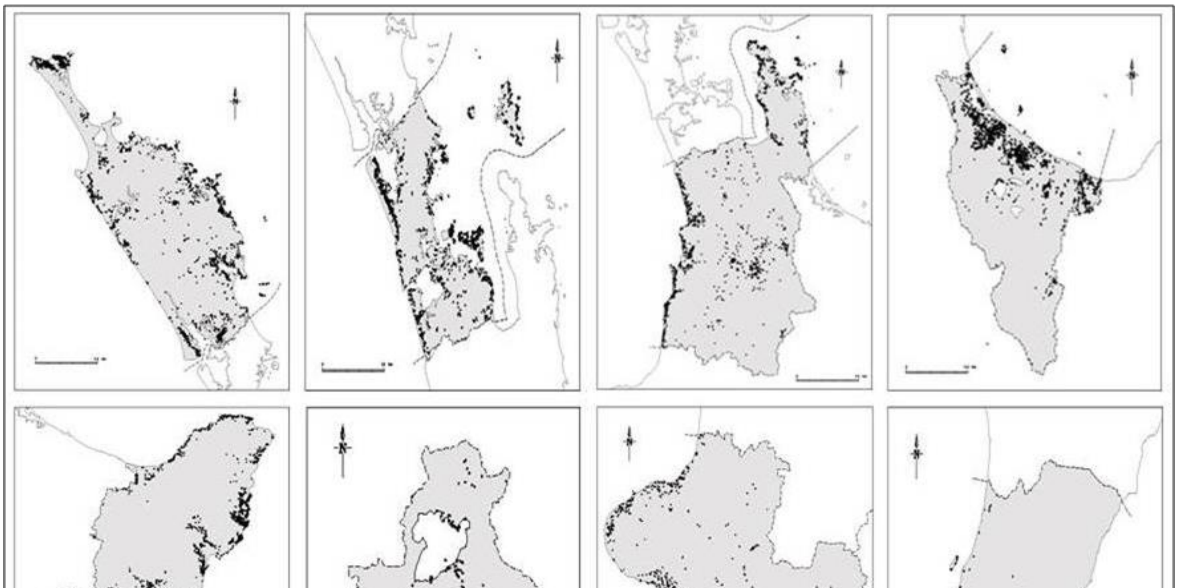


Map 2: *Kūmara cultivation areas during the expansion and retreat phases: Source: (Anderson, 2016; Burtenshaw & Harris, 2007)*

Despite the retreat of kūmara cultivation, the size of Māori cultivation sites increased in central and northern Aotearoa. As an example, the largest pre-European cultivation site ever recorded in Aotearoa was approximately 3,000 to 4,000 hectares. The site was located in the Waikato and consisted of 500 gardening plots located next to the Waikato and Waipa rivers and had 200 pā sites located nearby on the riverbanks (Anderson, 2016). The entire gardening area had its soil modified by adding sand and gravel from pits located near the gardens. To modify one hectare of soil would have required the digging, hauling, and spreading of 1,300 m^3 of sand gravel which equates to nearly 4,000,000 m^3 in total. Anderson (2016 p. 9) attempts to put that into a modern perspective:

> *"To appreciate how much that is, the floor slab for a 140 m^2 house will need about 16 m^3 of sand, gravel, and cement, so 4,000,000 m^3 = about 250,000 house slabs or four times the volume of the Clyde dam."*

The level of organisation, agronomic capability, and human effort required to complete a task of this size is significant. If a full survey of the area was able to be carried out it is believed that a growing site of 1,000 plots, double the number currently surveyed, could be found (Anderson, 2016). Map 3 illustrates the distribution of kūmara storage pits following the retreat phase.



Map 3: *Distribution of kūmara storage pit sites, post-retreat phase. Source: (Furey, 2006)*

2.5.4 The Quantity and Quality of Māori Horticulture

The three-stage development of kūmara cultivation created growing practices that produced crop yields that matched similar growing undertakings in the European world at a corresponding time. Research has determined that pre-European Māori growing practices were able to produce kūmara yields that are similar to and in some cases superior to contemporary New Zealand and world averages. Burtenshaw and Harris (2007) established two experimental kūmara cultivation sites that used traditional Māori growing practices to determine the yield of the kūmara cultivar 'Taputini' which was cultivated by pre-European Māori. After six growing seasons at the Robin Hood Bay site in Marlborough and the Whatarangi site in the Wellington region, they produced an average of 8.8 and 13.8 tonnes per hectare per annum respectively (Burtenshaw & Harris, 2007). Table 2 provides a comparison of the average yield results with the average yield in New Zealand and the world during the same years that the trials were conducted and with the most recent yield data as reported by the Food and Agriculture Organization (FAO).

Table 2: *Comparison of kūmara-sweet potato yields, average tonnes per hectare: Source: Adapted from (Burtenshaw & Harris, 2007; (FAO, 2021)*

Year	Robin Hood	Whatarangi	New Zealand	World
2000-01	7.0	12.2	14.4	9.3
2001-02	15.0	9.8	14.5	9.3
2002-03	6.6	14.1	16.2	9.3
2003-04	13.7	26.3	16.9	9.3
2004-05	4.9	8.2	16.6	8.9
2005-06	5.5	12.3	11.9	9.6
Average	8.8	13.8	15.1	9.3
2013			10.9	11.1
2014			10.5	11.3
2015			10.5	11.4
2016			10.5	11.5
2017			10.3	11.8
2018			10.2	11.3
Average			10.5	11.4

The growing conditions in the Northern Sea area of Europe are favourable enough that even children had little difficulty in cultivating successful potato (*Solanum tuberosum*) crops (Zuckerman, 1999). Despite the kūmara generally producing a lower yield than potatoes that are grown in the same conditions, the adaption of growing practices by Māori enabled them to produce yields of kūmara in temperate Aotearoa that were comparable to potato yields in pre-famine Ireland which Bourke (1968) estimates at 6 tonnes per acre (14.83 tonnes per hectare) (Bourke, 1968; Burtenshaw & Harris, 2007).

Not only were Māori able to produce good crop yields, but the nutritional quality of the food was also high. It has been argued that the physical living standard of Māori was at least equal, and in many cases better, than Europeans at the corresponding time which was in some measure due to the quality of diet (Coleman et al., 2005). The average age of death for pre-European Māori has been estimated at 31 – 32 years, and 45 years for Māori that survived to adulthood (Cambie & Ferguson, 2003; Coleman et al., 2005).

The average age of death in Europe, Asia, and America were similar to that of Māori at the corresponding time and this fact could also be attributed, at least partially, to the nutrient-rich diet of Māori (Cambie & Ferguson, 2003). Many of the nutrients, protective chemical constituents, and other health benefits of kūmara, taro (*Colocasia esculenta*), yam (*Oxalis tuberosa*), and the cabbage tree (*Cordyline terminalis*), all of which were traditional crops of pre-European Māori, have been identified. Table 3 provides a basic description of nutrients, chemical constituents and health benefits of kūmara, taro, yam, and the cabbage tree.

It could be viewed that the crop yield, physical living standard, and life span, are the all-important elements of crop growing outcomes. However, the Māori concept of kaitiakitanga requires a broader view, which view can be encapsulated by the phrase, “Ko ahau te taiao, ko te taiao ko ahau”. This phrase is typically translated as, “I am the environment, and the environment is me” (Rangiwai, 2018), another translation of this phrase is “The ecosystem defines my quality of life” (Harmsworth & Awatere, 2013). In Māori thought, an ecosystem is a dynamic relationship between humans, plants, animals, microorganisms, and the non-living environment in an interwoven functioning unit. Mauri is the life force or energy that permeates through this ecosystem and is the sustaining and animating force or energy of all living and non-living things (Marsden & Henare, 1992). The force or level of mauri within an ecosystem is tied directly to the health of that ecosystem, therefore damage or contamination of any part of it results in a loss of mauri (Harmsworth & Awatere, 2013).

Table 3: *Basic nutrient composition, chemical constituent, and health benefits of kūmara, taro, yam, and cabbage tree. Source: (Cambie & Ferguson, 2003)*

Nutrient	**Chemical Constituents**	**Health Benefits**
- Calcium - Iron - B vitamins - Carbohydrates - Fructose - Protein - Fibre - Fat	- Sporamins A & B - Scopoletin - Aesculetin - Umbelliferon - Cyanidin 3-glucoside - Pelargonidin 3-glucoside - Cyanidin 3-rhamnoside - Essential fatty acids	- Resistance to non-infectious disease. - Proteinase Inhibitor - Anti-cancer - Anti-coagulant - Antioxidant - Anti-inflammatory - Anti cardiovascular disease - Improved eyesight

2.5.5 Māori Horticulture and the Environment

The interwoven nature of the ecosystem means that any shift in mauri in any feature of the ecosystem causes a shift in the mauri of the next most closely related feature which would eventually shift the mauri of the entire ecosystem (Harmsworth & Awatere, 2013). Therefore, the benefits humans receive from using the land, including crop yield, physical living standard, and life span, is not the only important element of crop growing but merely one component of many concerning the use of the land and its ecosystem. Further, because the ecosystem defines a person's quality of life if the land and water are polluted because of horticulture or agriculture, then the quality of a person’s life is reduced regardless of the quality of the food produced. This is true, not just in Māori thought, but also in the view of modern science (Bibi et al., 2016; Cai et al., 2019; Council, 2008; Kim, 2008; Steffan et al., 2018).

Humans affect the mauri of the entire ecosystem through land use and therefore have a responsibility to care for the system and address any negative or potentially negative effects to its mauri (Harmsworth & Awatere, 2013). The depth of the human relationship with the ecosystem, and therefore the depth of human responsibility to it, can perhaps be best understood by a simple recounting of whakapapa: Following the incubating times of Te Kore and darkness of Te Pō came mankind's primordial parents Papatūānuku, the Earth Mother, and Ranginui, the Sky Father. Papatūānuku and Ranginui had many children and all of them lived in darkness between their parents. One of the children, Tānenuiarangi, pushed his parents apart and ushered in Te Ao Mārama, the Word of Light. Tānenuiarangi formed the first woman, Hineahuone, from the flesh of his mother Papatūānuku, and procreated with her. From the procreation of Tānenuiarangi and Hineahuone came humankind. Tānenuiarangi’s previous sexual relationships had been with non-human partners and it is from these encounters that the flora and fauna of the world were created. It is from this whakapapa that Māori views all the features of the natural world as their senior relatives and why they view their relationship with the ecosystem as reciprocal and obligatory (Rangiwai, 2018). To meet that end, traditional Māori horticultural practices included highly structured practical strategies to protect and restore the mauri of the ecosystem (Miller, 2005).

The prohibition on the use of manure, animal by-products, and human waste in crop growing (Burtenshaw, 2010; Polack, 1978) is an example of a strategy employed by Māori to protect the mauri of the ecosystem. Science confirms that the application of animal waste to the soil can move both vertically and laterally through the soil and spread pathogens to plants, soil, water bodies, and humans (Mawdsley et al., 1995). The practice of rāhui prohibits the utilisation of a resource and is implemented when the mauri of a resource has been diminished or is threatened and needs time to recover (Miller, 2005). Rāhui, in the form of fallowing land, is an example of a strategy employed by Māori to restore the mauri of the soil by giving it time for its depleted nutrients and lost microbial population to be restored (Reid & Rout, 2020). Science confirms that this form of rāhui can restore soil fertility and microbiological diversity, and improve the soil's physical properties and moisture content (Farooq et al., 2019).

Under circumstances where fallowing is not effective in improving biodiversity the use of prescribed fire can speed up and improve the recovery of biodiversity to the land (Isbell et al., 2019). The use of prescribed fire by Māori is a central feature of horticultural practice and is used both for the clearing of land and the deliberate addition of wood ash to the soil for the specific purpose of restoring or improving the mauri of the soil (Burtenshaw, 2010).

The strategies used to restore and protect the mauri of the ecosystem may have been effective but that is not to say that negative impacts on the ecosystem were completely absent from Māori horticultural practices. The pre-European Māori population grew rapidly, probably at an annual rate of between 1 and 1.5% per annum (Coleman et al., 2005). By the year 1500, the population of Māori had grown to the point where large areas of forest needed to be cleared for horticulture. This practice led to the erosion of topsoil, followed by the siltation of waterways, which in turn impacted fish and other animals (Van Meijl, 1995). The clearing of land by fire was likely done on a small scale before extensive burning of the dryer lowland coastal areas was carried out. Once extensive burning had begun the incidence increased rapidly and caused large-scale deforestation. Prescribed fire combined with climate change, volcanism, and naturally ignited fires saw close to half of Aotearoa's original forest cover removed by the time of European settlement (Ewers et al., 2006; McGlone, 1989; Perry et al., 2012). Despite the widespread deforestation, the speed at which deforestation took place, and the rarity of forest recovery from man-made fire, Māori actions were not the dominant controlling factor in the environment (Fuller et al., 2015). To a large degree, the highly active tectonic and climatic regime of Aotearoa lessened the degree of Māori fire use, with few exceptions, on the environment concerning river catchments (Fuller et al., 2015).

2.5.6 Māori Hybrid Agriculture

When Tupaea arrived in Aotearoa, the Māori horticultural system was complex and highly productive. In addition to propagation, growing, and land preparation methodologies, Māori had developed an intricate set of practices that included plant selection and handing, crop storage, the identification of over 65 different types of soil, and had trained wild black-back gulls to eat garden pests (Hargreaves, 1963; Harmsworth & Roskruge, 2014; Hutching, 2006; Roskruge, 2011). Although horticulture was generally subsistence in nature many Māori groups produced a surplus and traded with other Māori. Coastal Māori would exchange seafood products with inland Māori for their forest food products (Petrie, 2013).

There were many European visitors to New Zealand from 1769 onwards that left plants, animals, and tools with the Māori but it was not until shortly after the arrival of Christian church missionaries in 1814 that Māori were actively exposed to European farming methods (Beattie & Stenhouse, 2007; Hargreaves, 1959). The formidable horticultural knowledge of the Māori allowed them to become experts in growing European introduced crops, such as potatoes, in a very short time (Roskruge, 2009). With specific reference to Māori using their existing cultivation skill Fitzpatrick (2004, p. 16-17) makes the following observation:

> *"The Māori almost certainly hold the record for the most rapid adoption of the potato as a food staple outside the Americas. With their long history as skilled cultivators of root vegetables, coupled with the intense constraints encountered trying to adapt a subtropical plant repertoire the colder regions of New Zealand, they were uniquely well placed to grasp the significance of the new Amerindian import. What took centuries in the introduction of the potato into Europe seems to have taken only decades in New Zealand. European explorers introduced it around 1770 and by 1805 'immense quantities' of potatoes were reportedly being produced by Māori in the northern Bay of Islands. By 1813, large Māori potato plantations were reported at Bluff, in the extreme south of the South Island…."*

By the time the first organised groups of Europeans, who intended to settle permanently, began to arrive in Aotearoa in 1840, Māori had already transformed themselves from horticulturalists to agriculturalists. Māori were farming animals, native crops, and introduced crops such as maize, wheat, and potatoes, and had developed these practices to the point where they supplied the settlers of Wellington, Nelson, and New Plymouth with the majority of their food (Burke, 2014).

The introduction of European practices changed Māori society and economy rapidly and permanently, but the introduction did not result in the assimilation of Māori into European practices or the replacement of Māori values and tikanga. Instead, at least at the beginning, European practices were adapted to traditional Māori ways of knowing and doing (Coleman et al., 2005; O'Sullivan & Dana, 2008; Schaniel, 2001). The adaptation of European practices led to Māori creating a hybrid agricultural system that was based on a “best of both worlds” approach (Hargreaves, 1959; Reid & Rout, 2016; Schaniel, 2001). For example, the spread of iron digging tools among Māori commenced in the 1810s and spread rapidly enough that by the 1830s they had become a standard feature of Māori practice and by the 1850s the use of a traditional wooden digging stick (ko) was rarely seen (Hargreaves, 1959; Schaniel, 2001). However, in many instances, the iron tools adapted by Māori were not used as intended by Europeans, with nails being used as chisels and larger agricultural implements being converted into weapons (Schaniel, 2001).

The agricultural tools that were adopted were used within a Māori valuing context and not necessarily in the manner that Europeans expected the tools to be used. Further, where necessary the tools were modified to best fit Māori values, for example, Māori replaced the long handle of the hoe with a short handle because this facilitated digging from a squatting position which was preferred over the European styled stooping position (Schaniel, 2001). The tools were also utilised in the field in the traditional method with groups of men working together in unison in a single field and not in the European method (Hargreaves, 1959; Schaniel, 2001). Also, even though Māori grew the introduced maize plant, the European growing methodology was rejected and instead of planting maize in rows, Māori planted it in the traditional clumping formation believing it to be the superior methodology (Hargreaves, 1959). The hybrid system was used to grow both traditional and introduced crops and produce yields that were comparable to yields in the North Sea area of Europe and superior to those produced by European settlers (Horrocks et al., 2008; Petrie, 2002; van Bavel & Thoen, 1999).

While some European practices were adopted, Māori also entirely rejected others despite the encouragement from Europeans and their bewilderment at their rejection. For example, even though Māori owned and had been riding horses since at least the mid-1850s, many refused to use them to pull ploughs. Also, the use of animal bone dust and manure as fertiliser was a significant tapu issue which resulted in most Māori refusing to use either (Hargreaves, 1959; Linklater, 2013; Pool, 2015b; Schaniel, 2001).

2.5.7 The Growth and Domination of Māori Agriculture

The years from 1845 to 1860 have been described as the Golden Era of Māori agricultural enterprise (Francis, 2011). Māori crop growing grew rapidly and became large commercial enterprises which in one case saw a single cultivation area stretch 80.0 km along the banks of the Waipa river (Hargreaves, 1963). Table 4 provides data on the crop type and yield grown by Māori in the Lakes and Bay of Plenty district.

Table 4: *Māori crop production, Lakes and Bay of Plenty districts, 1857. Source: (Hargreaves, 1959).*

Crop	**Area (ha)**	**Average Yield (ha)**
Wheat	3,450	20 bushels
Potatoes	3.05	8 tonnes
Maize	1,735	40 bushels
Kūmara	1,230	8 tonnes
Garden & Orchard	118	-
Tobacco	16	-
Sown Grasses	7	-
Barley	4	-
Other Crops	110	-

Further, Swainson (1859, p. 65) provides a description of Māori agricultural assets in the Lakes and Bay of Plenty area:

> *"In the year 1857, the natives of these districts alone had upwards of 3,000 acres [1,214 hectares] of land in wheat, 3,000 acres [1,214 hectares] in potatoes, nearly 2,000 acres [809 hectares] in maize and upwards of 1,000 [404 hectares] acres planted in kumeras [kūmara]. They owned nearly 1,000 horses, 200 head of cattle and 5,000 pigs, four watermills, and 96 plows. They were*

> *also the owners of 43 small coasting vessels, averaging nearly 20 tons each, and upwards of 900 canoes."*

Māori traded commercially with European settlers and visitors, and by 1805 the most commonly traded items were potatoes, pigs, timber, and flax (Fitzpatrick, 2004). Flax was the largest export item with the first export of sixty tonnes, valued at £2,600, leaving Aotearoa shores before 1818. By 1831 the flax exports peaked at 1,182. Tonnes (Petrie, 2002). The British Navy Board was the largest single purchaser of flax which purchased approximately 50 tons in 1826 to 800 tonnes in 1832 (Francis, 2011). Figures 9 and 10 provide data concerning the volume and value of flax exports to the British Navy Board between 1826 and 1836.

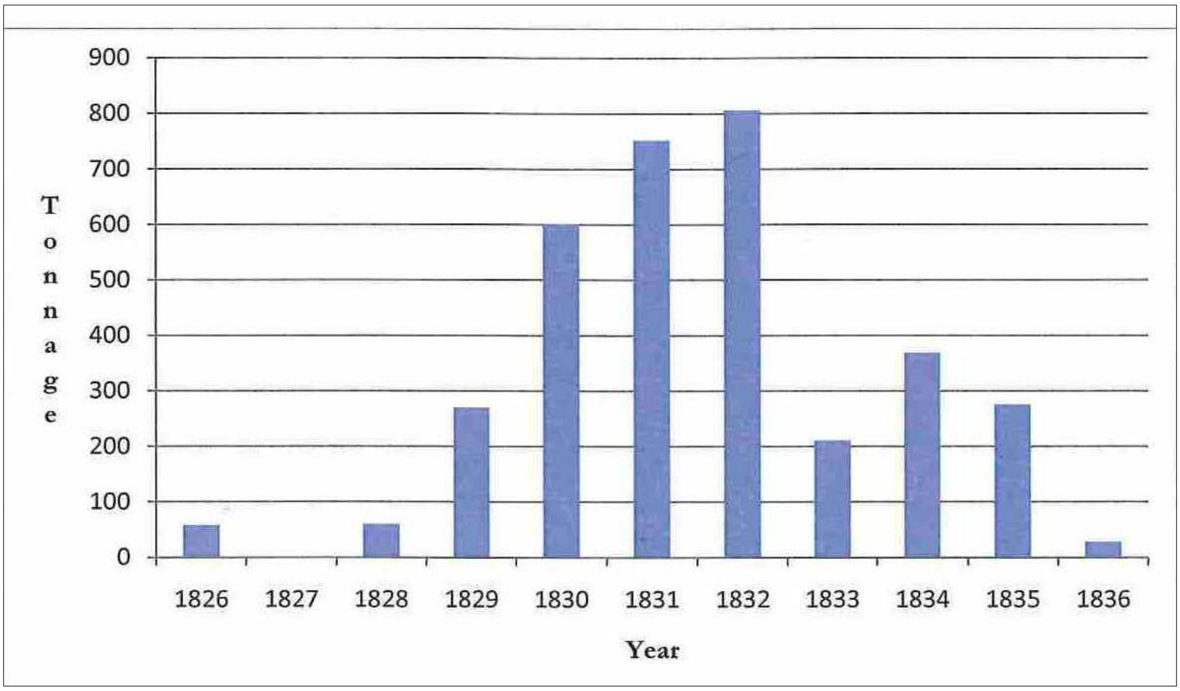


Figure 9: *The volume of flax exported from Aotearoa to the British Navy Board, 1826 to 1836. Source: (Francis, 2011)*

At its peak, flax was the largest export in New Zealand until wool and mutton exports began in the 1850s and 1880s respectively. By 1833, timber had become the largest export earner for Māori in the short term (Petrie, 2002).

The introduction of hardier European crops allowed for the cultivation of trade goods, and direct trade opportunities, across the entire country because unlike the kūmara, which can only grow in select regions, the potato could be grown from Northland to the Foveaux Strait (Wood, 2003).

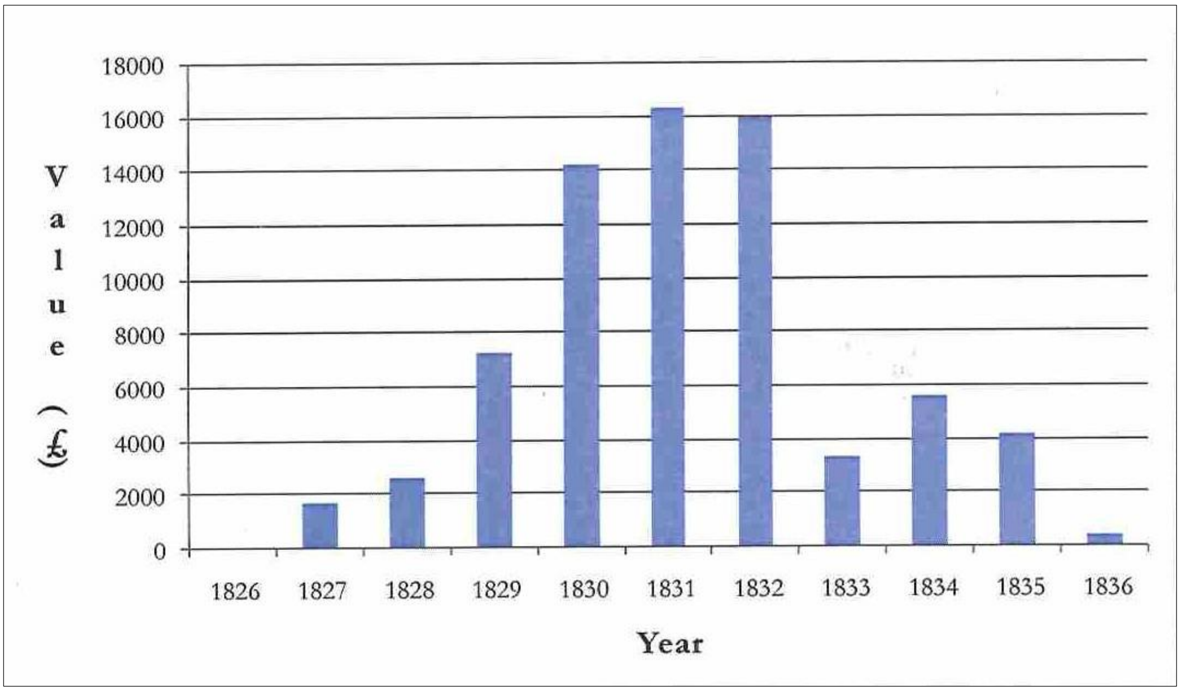


Figure 10: *The value of flax exports from Aotearoa to the British Navy Board, 1826 to 1836. Source: (Francis, 2011)*

The economic principle of supply and demand was clearly understood by Māori who selected the type, timing, and size of crop cultivation on the expected demand of European settlers and visiting ships. Some Europeans were surprised at the degree of skill that Māori displayed in the subtleties of commerce and their appreciation of the fact that scarcity and utility determined the value of commodities (King et al., 2017; Petrie, 2013).

Despite their appreciation for and ability to understand and operate within a European economic system, Māori did not necessarily adopt all the ethics of the system as evidenced by Māori not accumulating large amounts of unused capital but instead finding uses for that capital (Coleman et al., 2005). It is clear that Māori were skilled, motivated, and innovative entrepreneurs who were proficient in the European style of commerce and maximising returns and expanding their commercial operations (Petrie, 2013). However, as pointed out by Sowell (2016, p. 30) the geography of a country can either aid or constrain the social and economic opportunities and development of its people.

> *"The economic effects of geographic differences are both direct, affecting the standards of living, and indirect, affecting the development of peoples*

> *themselves, depending on whether a given geographic setting facilitates or impedes their communication and interactions with the rest of the human race…to be in touch with what other peoples around the world are doing has been a major advantage, and to be isolated a major disadvantage."*

One of the most important geographical factors is oceans which were once major barriers to communication and interaction with other regions of the world (Sowell, 2016). By seeing how things can be done differently, people can break the process of doing the same things the same way for generations or even centuries, as can happen in geographically isolated societies (Sowell, 2016). The economic capability, development, and opportunity improved significantly by the introduction of European technology, farming practices, and trade opportunities. With their ability to adapt European technology and farming practices for their use Māori quickly became the dominant producers of agricultural goods (Petrie, 2013). This domination could be explained by the fact that the Māori population was much larger than the settler population and because Māori had the greater majority of land, however, the domination continued until well after those advantages were no longer extant (Petrie, 2002). Figure 11 shows the population comparison between Māori and Europeans in Aotearoa-New Zealand. Reference to the data supports Petrie's (2002) observation that agricultural domination may not have been entirely due to Māori having a larger population.

With their newfound ability to cross oceans in European shipping vessels, Māori economic opportunities expanded internationally. Māori travelled to the Pacific Islands, Australia, North America, South America, Asia, and Europe where they were exposed to these markets, products, technologies, and economic systems. The crossing of oceans also allowed Māori to bring innovations to Aotearoa in the form of wheat cultivation and commercial dairy farming, of which, Māori were the first to establish in Aotearoa (Petrie, 2002; Phillips et al., 2014).

With commercial success came the ability to purchase ships and to invest heavily in one of the most advanced agricultural technologies in the world at the time -

water-powered flour mills (Petrie, 2013). Map 4 provides data on the number and location of flour mills in the Waikato district.

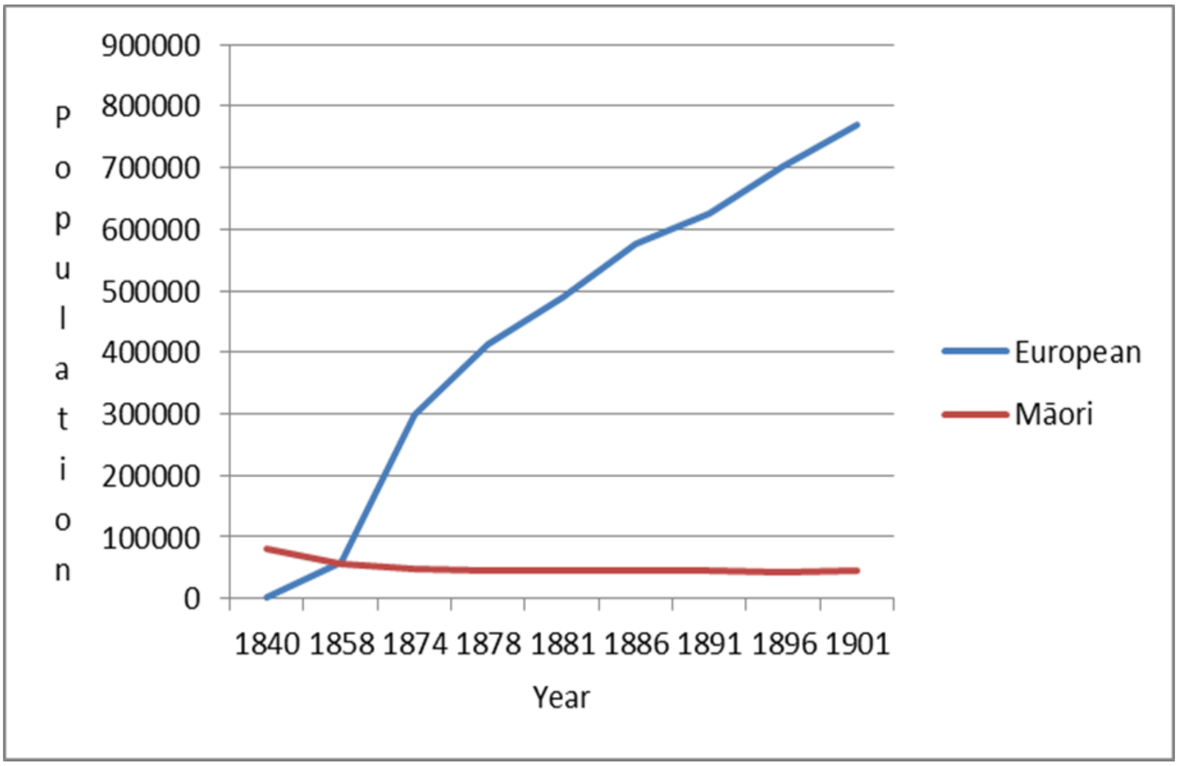
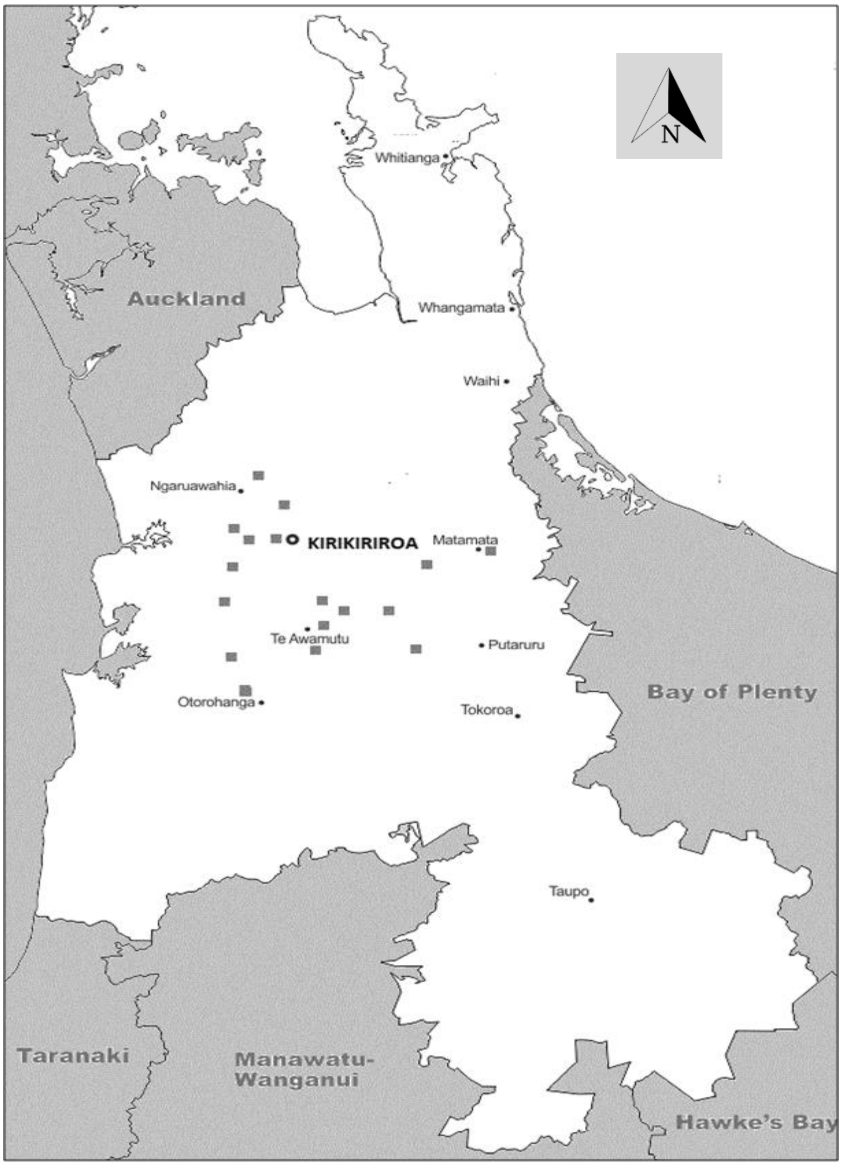


Figure 11: *The population of Māori and Europeans in Aotearoa-New Zealand from 1842 to 1901. Source: (Orange, 2012)*

The expansion of Māori commerce was achieved with deliberate intention and strategies that included overseas travel where diplomatic and trading relationships were formed in person with sitting monarchs, governors, and merchants (Petrie, 2013).

During the growth and domination era, Māori rose to be the dominant economic force in Aotearoa and the main source of government revenue (Hart, 2016). Until income tax was introduced to Aotearoa-New Zealand, customs duty was the largest contributor to government revenue of which Māori contributed approximately £50,000 per annum or around 30% more than Europeans (Hart, 2016; Petrie, 2013).

Māori owned and worked the most productive land in the country and supplied the majority of goods to the local market and dominated the supply of agricultural commodities to the export market. Māori owned flour mills, sailing ships, livestock, beasts of burden, wagons and carriages, timber mills, and infrastructure. Māori also boasted productive relationships with European-owned banks, and Waikato Māori established their own trading bank (Francis, 2011), and had strong reputations as ndustrious, innovative, and capable businessmen. Māori were prospering and were successful agriculturalists but it would not last long.

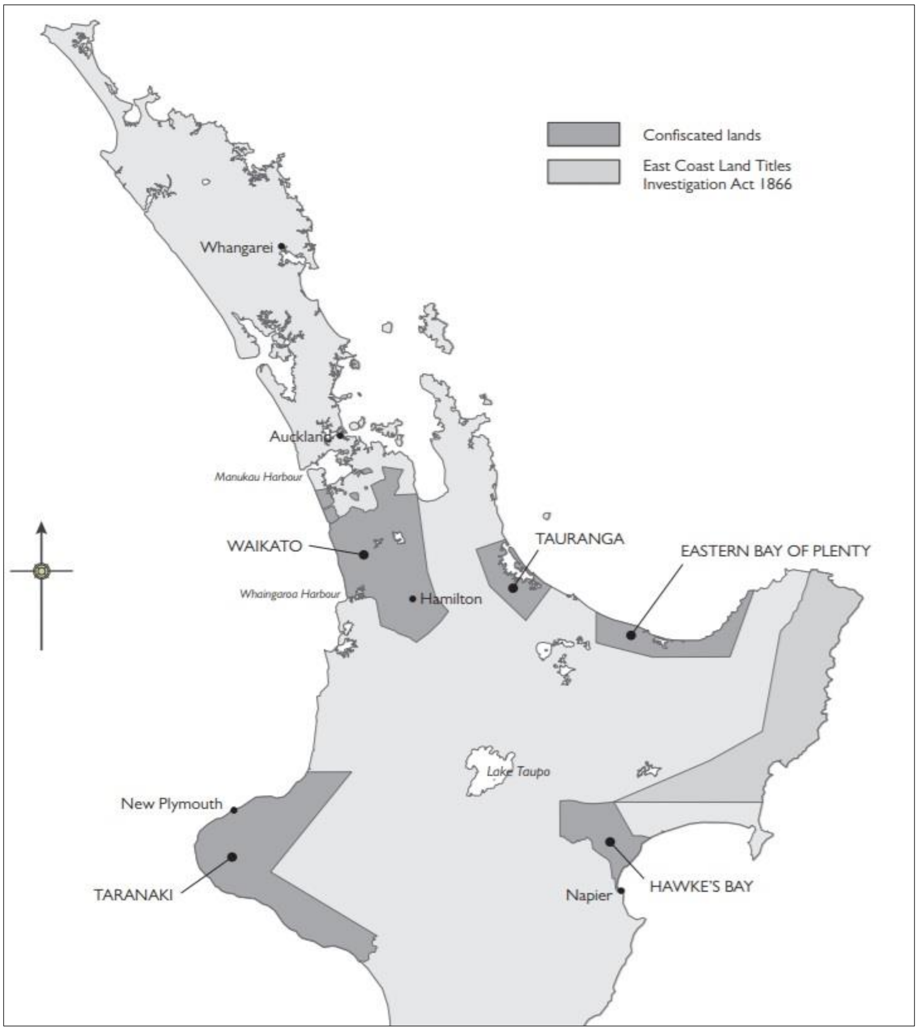


Map 4: *Locations of the water-powered flour mills in the Waikato, 1853. Source: (Hargreaves, 1959)*

2.5.8 The Decline and Collapse of Māori Agriculture

Within two generations of Tupaea's arrival in 1769, Māori were able to expand their traditional subsistence horticulture to being large-scale broad-acre producers of an array of high-quality agricultural products. Māori supplied both domestic and export markets, almost to the total exclusion of their European competitors (Wood, 2003). However, within the space of a single generation, Māori had not only lost their position as the dominant producers of agricultural goods, but they also began to lose some of their traditional agricultural practices including aspects of kaitiakitanga (Hargreaves, 1959; Petrie, 2002).

The occupation and control of land was not the sole reason for the colonial government instigating war against Māori (Wood et al., 2008). However, the New Zealand Wars were the pretence used by the colonial government to confiscate close to 1.4 million hectares of Māori land (Boast & Hill, 2010; Gilling, 2020). The land confiscated by the colonial government was the most fertile and productive land that was located in areas best suited for agriculture and trade (Clydesdale, 2007; O'Malley, 2016). Map 5 illustrates the areas that were confiscated by the crown. There were six main areas of confiscation, Waikato, Taranaki, Bay of Plenty, Hawkes Bay, East Coat, and Tauranga.



Map 5: *Land confiscated from Māori by the crown. Source: (O'Malley, 2018).*

The brutality of the New Zealand Wars and the loss of land are often cited as the primary reasons for the collapse of Māori agriculture (Harris, 2006). However, the decline started some years before the wars and this pre-war and pre-confiscation period did not stop the decline (Consedine, 2007; Francis, 2011; Wood et al., 2008). The eventual collapse of Māori agriculture was probably inevitable with or without war (Furey, 2006; Hargreaves, 1960; Wood et al., 2008) and Harris (2006, pg. 19-20) discusses five reasons for the decline and collapse that does not involve the New Zealand Wars or confiscation, a five-point summary is:

1. Māori were not able to shift their cultivation to new land.
2. Yields and crop quality decreased because of the use of low-grade seed.
3. Cultivation was no longer aligned to maramataka and crops were planted at the wrong time which frequently resulted in crop failure.
4. Markets for Māori products collapsed.
5. Māori began to purchase their food rather than growing their own crops.

While the wars certainly accelerated the collapse and ended any hope of recovery (Hargreaves, 1960; Petrie, 2013), there was no single reason for the collapse but rather a combination of many factors as pointed out by Harris (2006). It is not the purpose of this study to detail all the complexities of the decline and collapse but several factors are directly relevant to this study that involve cultivation productivity and kaitiakitanga practices, which are discussed below.

During the late 1850s and early 1860s, Māori were becoming more aware of the unfavourable effects of colonisation which led to a rise in Māori nationalism (Francis, 2011; Petrie, 2002; Wood, 2003). The increasing nationalism led some to reject and abandon European technology, including agricultural practices, and reverting to traditional methods (Francis, 2011; Hargreaves, 1959; Segell, 2018).

However, due to Europeans now controlling large areas of agricultural land it became impossible for some Māori to reintroduce important pre-European farming practices in their entirety. The encroachment of European-controlled land meant that many Māori could not implement rāhui, fallow their land, and move to more fertile areas (Hargreaves, 1960; Harris, 2006). This also meant that the practice of prescribed burning was not always possible which in turn would deprive the exhausted soil of the restoration of its physical and chemical properties that it requires to grow high-yielding and high-quality crops. The problem with soil fertility was exacerbated by the cultivation of potatoes. A potato crop requires five times more N than a kūmara crop, therefore the following of land in the traditional timeframes did not give the soil sufficient time to recover (Wood, 2003).

Māori had invested heavily in farming equipment and infrastructure since transitioning from horticulturalists to agriculturalists. However, between 1857 and 1860 approximately £50,000 of Māori capital that normally would have been invested in agriculture was spent on muskets (Hargreaves, 1959; Sinclair, 1952). The diversion of capital away from agriculture resulted in land not being cultivated and agricultural operations being neglected to the extent that by 1858 Māori were having to purchase large amounts of flour from Europeans (Hargreaves, 1959; Wood, 2003).

The neglect of agricultural farms and enterprises was not due solely to the lack of capital investment. The standard of growing practices had declined to a level that only a few years previously would have been unheard of (Hargreaves, 1959). Flax, which had been grown in Te Rohe Pōtae, in the King Country district, had comprised up to 67% of the value of exports leaving New Zealand (Francis, 2011). However, even before the New Zealand Wars and land confiscation, Te Rohe Pōtae flax exports had dropped by 89% due to a lack of quality. The Royal Navy, the largest single purchaser of Māori flax, cancelled a lucrative contract due to the poor quality of the finished product (Francis, 2011). By the mid-1850s the quality of flour, another important trade commodity, had deteriorated to the point that it sold for less than the second-grade flour produced by Europeans, and by the late 1850s, the wheat exported to Australia was also of low quality (Francis, 2011; Wood, 2003). The three primary reasons for the low-quality flour were 1) the continued use of the same soil, without the use of rāhui to restore fertility, which led to its exhaustion, 2) weeds were frequently allowed to grow within wheat crops and were milled together, and 3) the continued use of old, unclean, and even diseased seed (Francis, 2011; Hargreaves, 1959; Wood, 2003). While demand for potatoes in the mid-1850s increased in the Auckland region, a large proportion of Māori potatoes were considered to be of insufficient quality for the

Auckland market. The lack of sufficient quality was due largely to the use of poor quality seed (Francis, 2011; Hargreaves, 1959).

By the late 1850s while some cultivation sites, particularly in Northland, the Auckland peninsula, and Rangiaowhia in the Waikato, maintained good practices and high-quality products, many cultivation sites around the North Island were regularly found to be untidy, lacking planning, full of weeds, and with crops being ruined by caterpillars and disease (Consedine, 2007; Hargreaves, 1959). The declining standard in growing practices led to a decline in yield and in the quality of crops, which became increasingly diseased and infected with pests such as wireworm (*Agriotes lineatus*) (Francis, 2011; Hargreaves, 1959). Consequently, Māori grown products were no longer in demand, fetched lower prices than European products, and in some cases could not be sold at all (Hargreaves, 1959; Wood, 2003).

The export and domestic markets that had been purchasing a large proportion of Māori goods had become more self-sufficient and capable of producing their own food which meant that the demand for even high-quality Māori products was in steady decline (Burke, 2014; O'Sullivan & Dana, 2008). Also, there was greater competition from international suppliers who were also able to offer goods at a lower price than offered by Māori (Wood, 2003). The lower prices available from international suppliers completely reversed the wheat trade in Aotearoa as demonstrated by the volume of wheat being handled in Auckland, the principal port for Māori products, going from being largely export-based to being largely import-based (Francis, 2011; Wood, 2003). Many European settlers also resented the tremendous commercial success of Māori and Māori ability to keep settlers out of the market by undercutting them, and that resentment led to the settlers seeking to remove Māori goods from the market and importing goods rather than contributing to Māori economic success (King et al., 2017; Petrie, 2002). Māori clearly understood that land was the foundation of wealth creation and this understanding reduced their willingness to sell land. This reluctance to sell land led to significant resentment among settlers and government officials and ultimately led to the New Zealand Wars (King et al., 2017).

Tapu in agriculture was observed in large measure among Māori up to the 1830s in the Bay of Islands and into the 1840s in other areas of Aotearoa-New Zealand. Crops were placed under the protection of atua through tapu and despite the efforts of Christian missionaries even Europeans were made to recognise the prohibitions of this form of tapu. This was true even in areas, such as Rangihoua, where Māori had close associations with missionaries (Hargreaves, 1963). Hargreaves (1963, p. 113) suggests that whether consciously or unconsciously all European engaged in the activity of destroying the Māori system of tapu and that the Europeans achieved some success:

> “The breaking down of tapu was undertaken consciously and unconsciously by all Europeans whether missionaries or laymen. In some ways, and in limited areas, success was achieved, for example in the Kerikeri area where eating in houses, previously unheard of among the Māoris, was quite common by 1826.”

While Hargreaves (1963) contends that all Europeans were involved in the attempted breaking down of tapu he singles out Christian missionaries as being particularly involved in this activity. By the mid-1840s many tapu restrictions were no longer strictly observed even by tribes that had refused to be taught Christianity. The younger generation of Māori rebelled against many tapu practices and this contributed to breaking down tapu more than any other factor (Hargreaves, 1963).

However, despite sustained attempts by missionaries and government agents to get Māori to use animal manure in their agricultural practices, Māori for the most part refused (Hargreaves, 1963; Wood, 2003). Missionary and government officials then began encouraging Māori to take up pastoral farming (Wood, 2003). However, except for a small number of Māori in Northland not many Māori followed the government's encouraged pathway but instead looked upon animal farming as a wasteful effort believing that sheep and dairy cattle took much more effort and care than pigs and semi-feral cattle that could, for the most part, take care of themselves. Some Waikato Māori also purchased livestock and the government provided loans to purchase grass seed and additional sheep. However, these activities were stopped by Pōtatau Te Wherowhero, the first Māori King, who discouraged pastoral farming. Te

Wherowhero believed that the loans would entitle the government to lay a financial claim on the land and that the conversion of crops to pasture would only encourage Europeans to try and take control of the land (Wood, 2003).

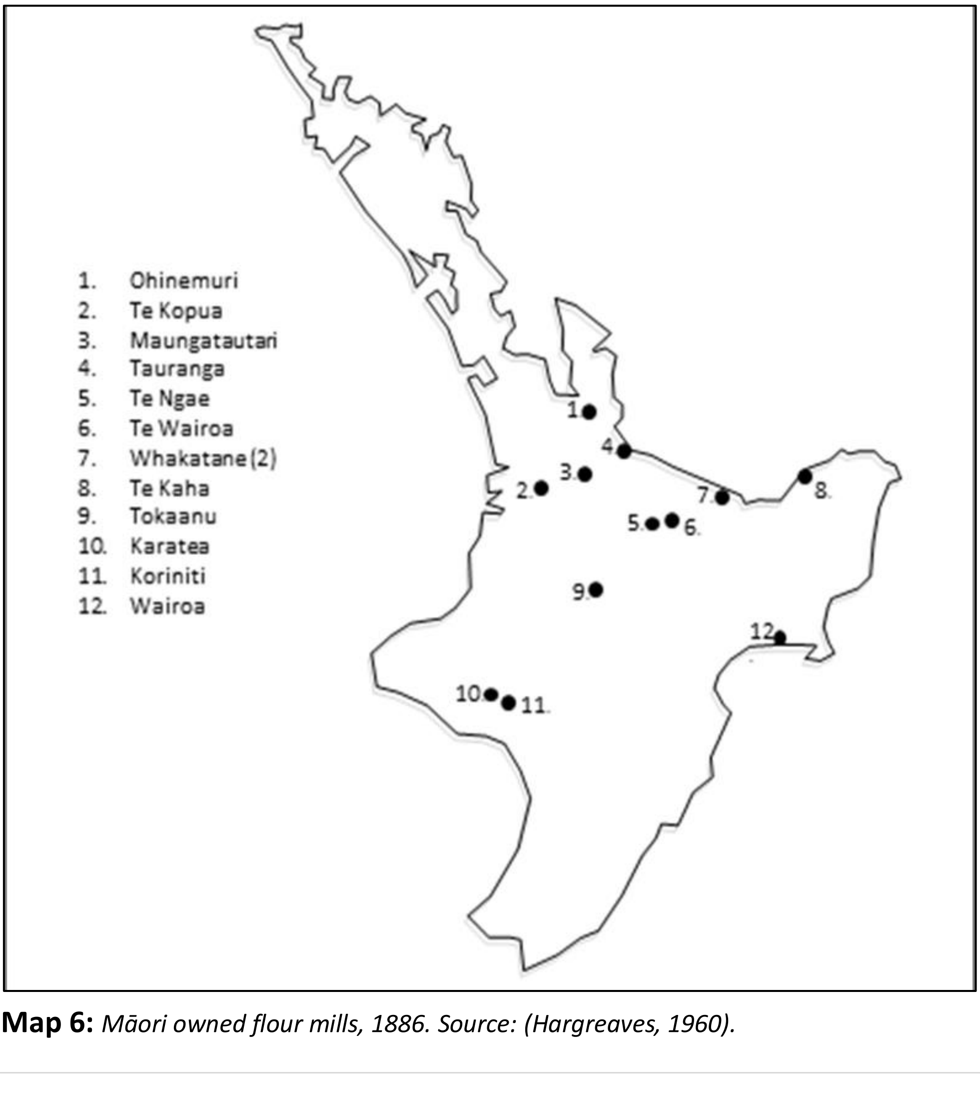
Regardless of whether the land was used for crops or pasture, Europeans wanted the land and used what became known as the New Zealand Wars as the pretext to take the land (Belich, 2013; Boast & Hill, 2010). A lack of capital investment, a change in growing practices, declining yield and crop quality, a changing domestic and international market, and the inability to implement important cultural practices, including aspects of kaitiakitanga, were just some of the reasons for the decline in Māori agriculture. The New Zealand Wars and the confiscation of land were the final acts in the demise of Māori agriculture and the destruction of the Māori economic base (Johnson & Perley, 2015).

2.5.9 Māori Farming Post-New Zealand Wars

The New Zealand Wars, the accompanying land confiscation, loss of crops and livestock, and the destruction of agricultural infrastructures, such as flour mills, warehouses, trading ships, and hostelries, impacted Māori agriculture significantly (Petrie, 2015; Robinson, 2011). There are many differences of opinion among researchers regarding the post-New Zealand Wars progress of Māori agriculture (Francis, 2011). However, in general, Māori that lived in areas of land confiscation (see. Map 9) and large immigration of Europeans experienced hardships, poverty, and disease (Coleman et al., 2005; Francis, 2011). Crop production in these Māori settlements did little more than reach a subsistence level and little concern was given to the production of surplus trade items (Francis, 2011; Robinson, 2011). Outside of confiscation areas, Māori, in general, began to rebuild their agricultural platform and toward the end of the 1870s agricultural activity began to increase beyond local needs (Coleman et al., 2005; Robinson, 2011).

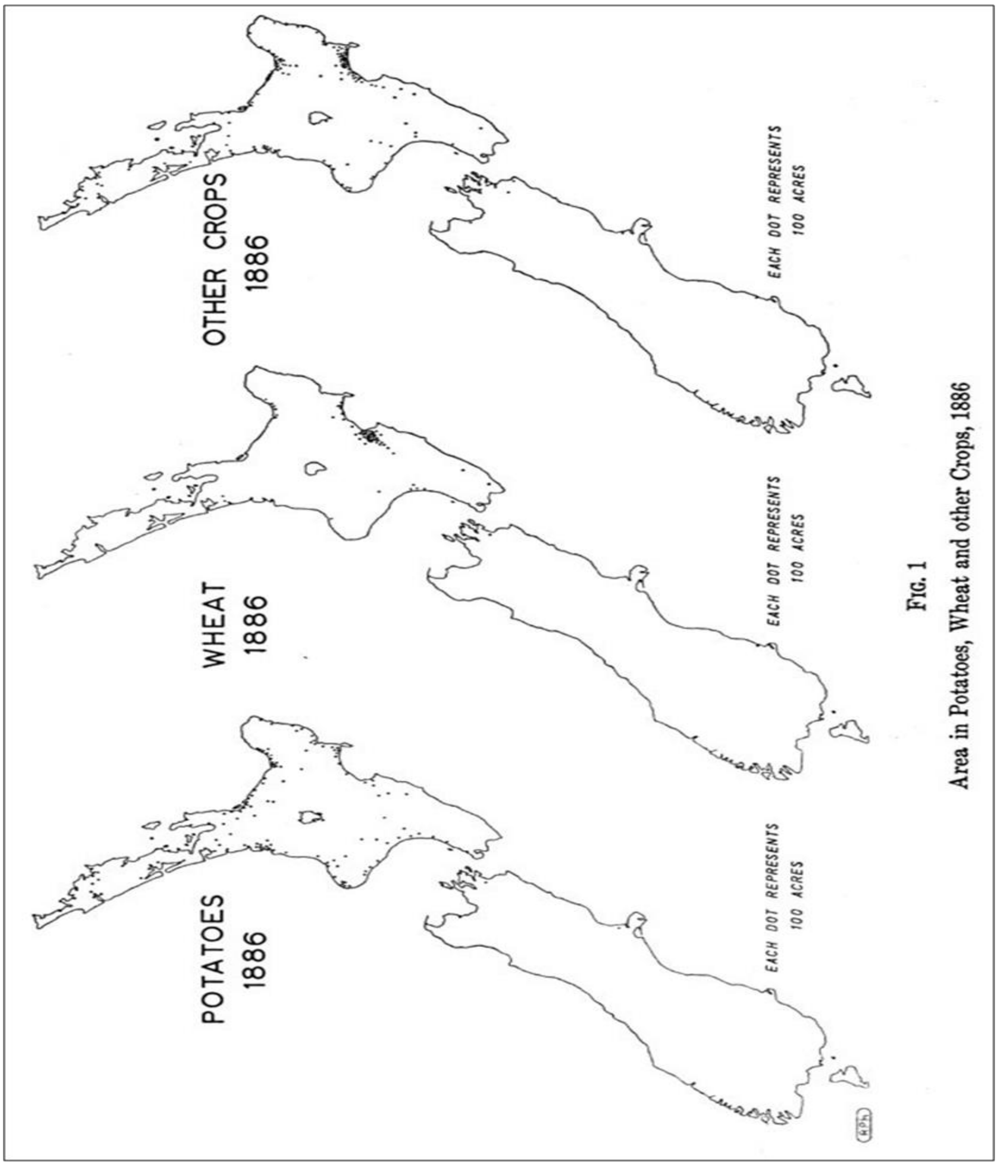
With markets generally receiving their goods from imports and colonial Europeans, another phase of Māori agricultural innovation commenced with the experimentation with new crops, extensive growing of crops that were previously grown on a limited scale, and greater involvement in rearing livestock (Coleman et al., 2005; Francis, 2011). While maize, potatoes, and kūmara were still the staple crops, Māori in all areas of the country, except for the King Country, began growing other crops such as hops, tobacco, mulberry, and even grapes which were sold to a German vineyard. Of the new crops, tobacco proved to be the most widely grown and was successful enough that very little tobacco was imported in the 1880s (Coleman et al., 2005; Hargreaves, 1960).

The 1886 census provided some detail regarding the cultivation and livestock farming that Māori undertook at this time. Wheat was the major crop grown by Māori with the Hawkes Bay district cultivating 2,600 hectares and producing 72,600 bushels of wheat. The Wairoa district produced up to 23,000 bushels of wheat which is milled in the districts Māori owned flour mill. Between the years of 1871 and 1886, 13 flour mills, including Wairoa, were owned by Māori. Map 6 illustrates the locations of the 13 Māori owned mills.



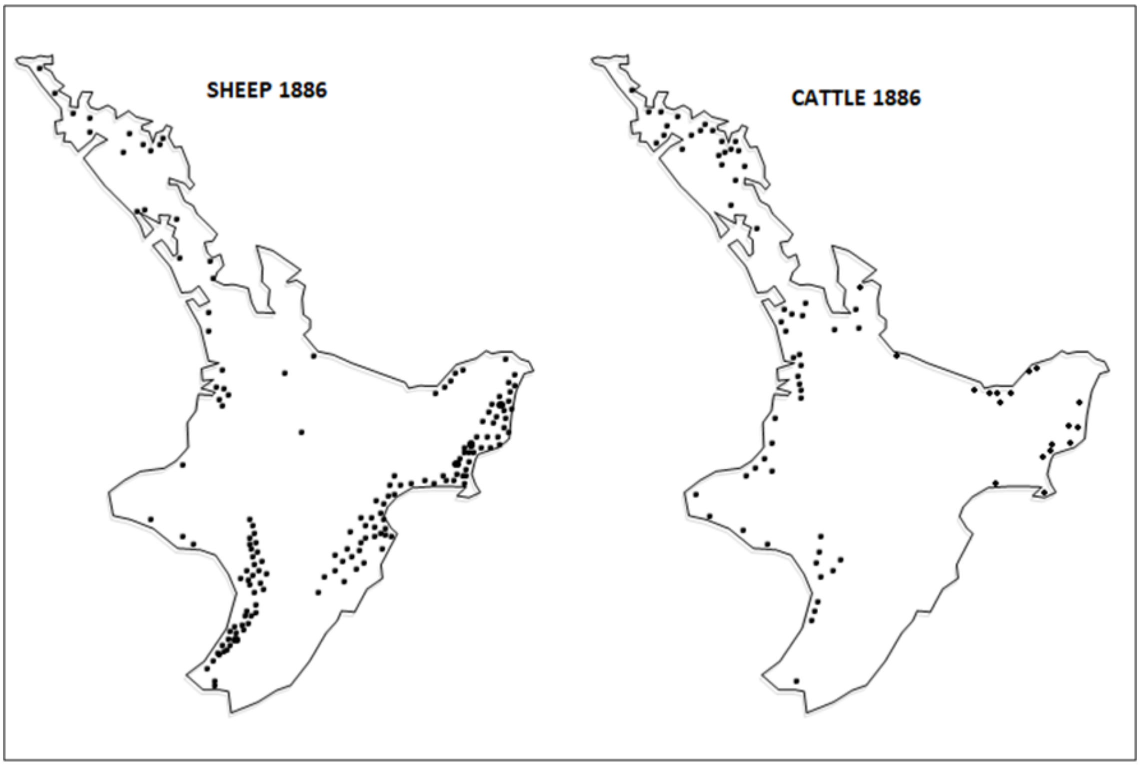
Map 6: *Māori owned flour mills, 1886. Source: (Hargreaves, 1960).*

The Bay of Plenty, East Coast, and Waikato grew oats, with the Hawkes Bay again being major growers with 8,000 bushels of oats. In the Northland district of Hokianga extensive cultivation of sorghum took place and tobacco was grown successfully throughout the North Island from Northland to Whanganui to Poverty Bay and the Urewera's. Hops were grown as far north as Hokianga, as far east as the East Coast, and as far south as Motueka (Coleman et al., 2005; Hargreaves, 1960; Robinson, 2011). Map 7 illustrates the areas where the major crops were grown in Aotearoa-New Zealand in 1886 according to census data.



Map 7: *Māori crop growing areas, 1886. Source: (Hargreaves, 1960)*

The traditional Māori livestock practices continued after the wars ended, wherein Māori primarily limited their practices to pigs and bush cattle that were semiwild and did not require fencing or pasture (Hargreaves, 1959). However, despite requiring greater care, including shearing, fencing, and the sowing of pasture, livestock farming began to be accepted more and more by Māori in the 1880s (Hargreaves, 1960). The 1886 census reveals that the East Coat and Manawatu Māori raised 112,850 sheep, 42,103 cattle, and 92,091 pigs (Coleman et al., 2005). This data seems to indicate that Māori farming practices had changed considerably from those of the 1850s. Previously, crop cultivation had been a significantly larger undertaking than livestock rearing but by 1886 livestock had become a major part of Māori agricultural practice. This level and type of livestock farming is a clear indication of a change not only in farming practices but also in farming attitudes among Māori (Coleman et al., 2005). Map 8 illustrates the areas where livestock farming was conducted in Aotearoa-New Zealand in 1886 according to census data.



Map 8: *Distribution of Māori sheep and cattle farms, 1886. Source: (Hargreaves, 1960)*

Although crop production levels had improved significantly from the early 1870s to the late 1880s they did not reach the levels of the 1840s or 1850s. During its peak production period, Māori exports of wheat experienced an eight-fold increase between 1853 and 1855 and were responsible during this period for up to 80% of Aotearoa-New Zealand's wheat exports. During this same period, Māori sales into the

Auckland region equalled almost 195,000 bushels of wheat, 70,000 bushels of maize, and 3,100 tonnes of potatoes from coastal and canoe deliveries alone (Hargreaves, 1959). However, even though production in the late 1880s did not meet previous levels, a surplus was produced and trade was conducted with European colonists (Francis, 2011).

Agriculture became sufficiently prosperous for Māori to again invest significant capital and purchase farm machinery, sailing vessels, and then steam-powered vessels, and rebuild destroyed and lost infrastructure (Francis, 2011). While some traditional farming practices were still used, Māori were using more European practices and increased their use of farm machinery. Hargreaves (1960, p. 363) makes the following observation:

> *"This was particularly noticeable in the greatly increased use of machinery. Except in the more remote areas of the King Country and the Urewera, the plough was in almost universal use, and to a lesser extent harrows, carts and drays. Many tribes possessed reaping, threshing and winnowing machines, and in the earlier years, one tribe in the Marton area owned a stream thresher which they hired out to their European neighbours, it being the only one in the district."*

Despite public disapproval, the colonial government provided help to restore the Māori agricultural economy. Hargreaves (1960, p. 11) makes the following observations:

> *"This was mainly in the form of agricultural implements such as ploughs, harrows, carts, and even such relatively expensive items as threshing machines…In the financial year 1874-75 for example a total sum of £774 7s 3d was spent by the Government on agricultural implements for different Māori tribes."*

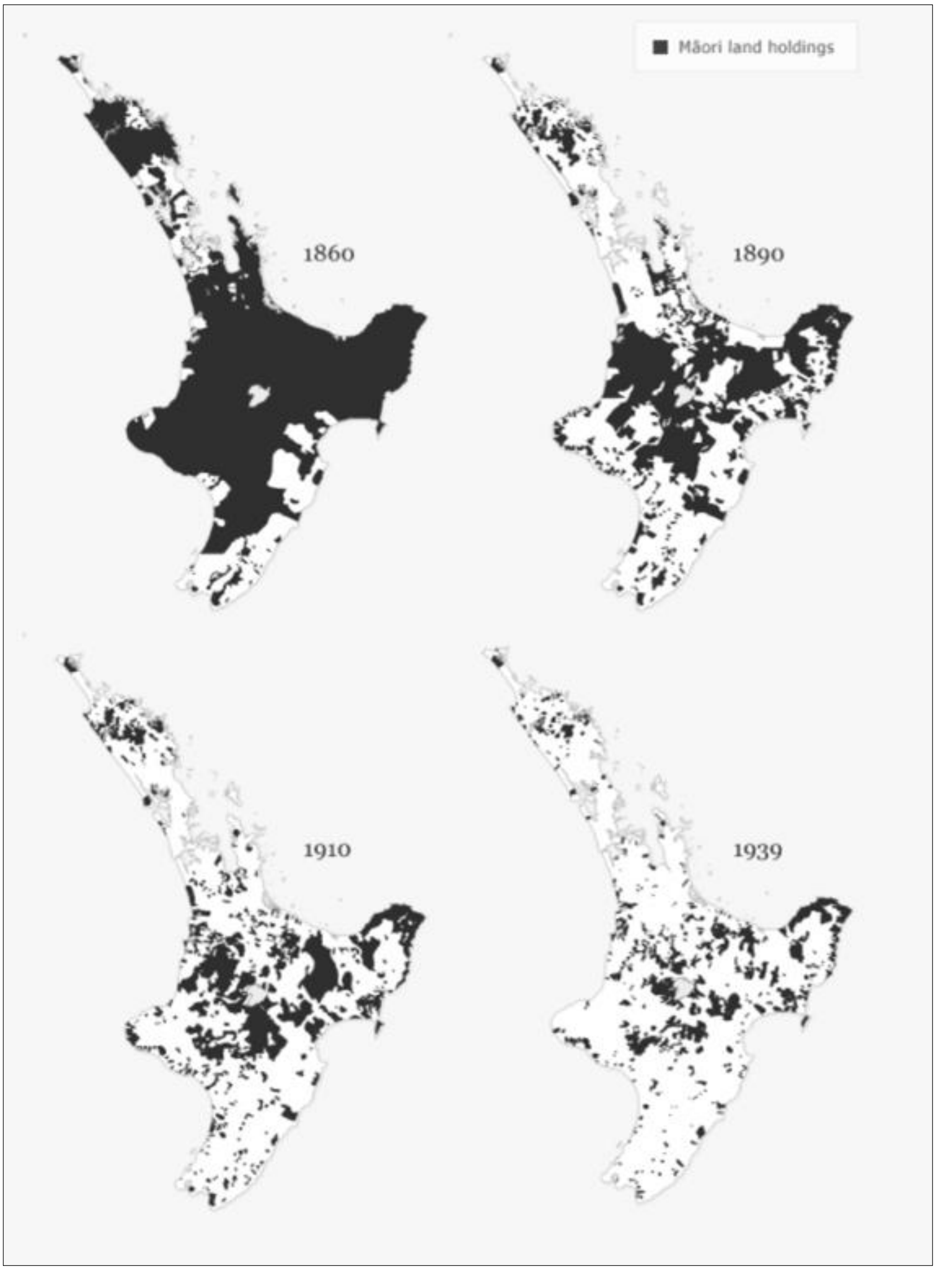
The government of the day also provided wheat, oat, grass, and other seeds, and also provided financial help in restoring or building infrastructures such as water-powered flour mills and fencing (Hargreaves, 1960).

In 1907 the ‘Stout-Ngata Commission’ was established wherein Āpirana Ngata and Robert Stout were tasked with identifying what Māori land could be offered to Europeans to buy or lease for agricultural purposes, and what land Māori should be allowed to keep (Walkinton, 1998). The commission reported that the Government had a duty to provide Māori financial support so that they could successfully farm their own lands but this recommendation was largely ignored (Walkinton, 1998). Government assistance had been available to farmers since the establishment of the Department of Agriculture in 1891 and the Advances to Settlers Act of 1894. However, this assistance was generally only available to individual owners and therefore not of use to Māori whose landholdings were communal (Consedine, 2007). In 1928, Āpirana Ngata became the Minister of Māori Affairs and he implemented land development schemes for Māori relative to Section 23 of the Native Land Amendment and Native Land Claims Adjustment Act 1929 (Gould, 2004). The purpose of the development scheme was described in section 23(1) of the Act as being the:

> *“…better settlement and more effective utilization of Native land or land owned or occupied by Natives, and the encouragement of Natives in the promotion of agricultural pursuits and of efforts of industry and self-help”.*

However, by 1935 Ngata had resigned, the administration of the scheme was carried out largely by European staff, and the emphasis of Māori land development was “moved away from serving the peculiar needs of rural Māori towards the efficient use of the land for the “national good” (Gould, 2004). The development scheme was tightly constrained by European bureaucracy and the focus moved from land development to concerns about recouping the finance advanced to Māori landowners as part of the scheme (Tribunal, 2004). Despite all the bureaucratic roadblocks to Ngata’s vision of the development scheme providing a working economic base for Māori, the largest obstacle was that Māori did not have enough land to provide themselves with even reasonable prosperity (Tribunal, 2004).

By the 1910s Māori owned less than 1% of South Island, most of it having been confiscated in 1865, and 25% of North Island (Ministry for Culture and Heritage, 2016). A large proportion of the land that remained in Māori ownership was not suitable for agriculture and was incapable of providing an economic base for owners (Consedine, 2007). Map 9 illustrates Māori land holdings from 1860 to 1939. The diagrams in Map 9 reflect confiscated land, both compulsory and voluntary crown acquisitions, and private acquisitions.



Map 9: *Māori land holdings, 1860 – 1939, represented by dark areas. Source: (Orange, 2012)*

2.5.10 Contemporary Māori Farming

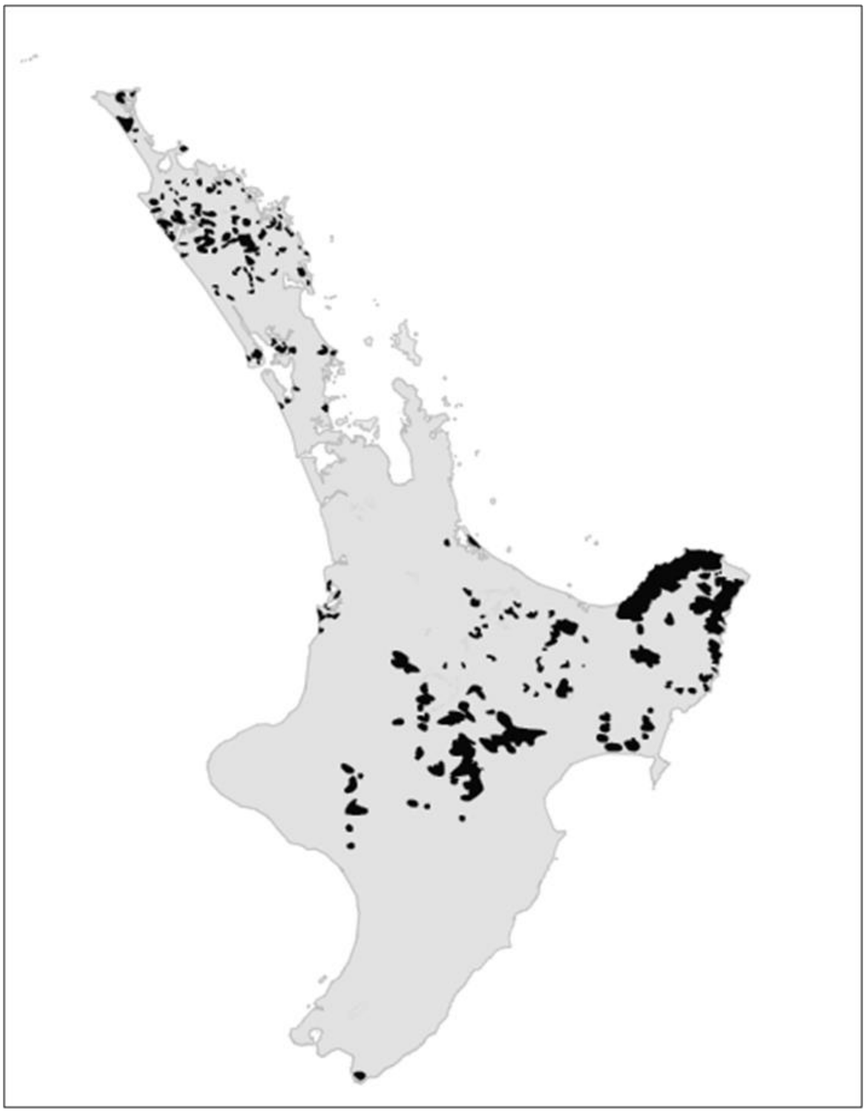
Although it has oftentimes been reluctantly given, if not out rightly ignored or misrepresented, the recognition Māori have received as highly skilled agriculturalists, business persons, and contributors to the economy are deserved (Petrie, 2015). However, despite their ability to revive agricultural production and trade in the post-war era, under adverse and undermining political conditions, there is no level of skill that can compensate for the lack of suitable land and the inability to use key crop growing practices. (Gould, 2004)

Instead of concentrating primarily on crop growing as did their forbears, contemporary Māori farmers are predominantly pastoralists with just over 50% of their farms dedicated to grassland (Johnson & Perley, 2015; Statistics, 2016). Māori dairy farmers produce around 8 – 10% of the national milk solids and 10 – 15% of the national sheep and beef units (Kingi, 2020).

By 1996 Māori landholding has been reduced to approximately 1.5 million hectares or 5% of the total land areas of Aotearoa-New Zealand. Of that 1.5 million hectares 20%, or 300,000 hectares, is considered to be productive agricultural land with the remainder considered to be under-utilised or under-performing (Kingi, 2020). Table 5 provides the total amount of land owned by Māori from 1840 to 1996 and Map 10 illustrates the geographical areas of Māori land as of the year 2000.

Table 5: *Area of Māori owned land 1840 – 1996. Source: (Carswell et al., 2002; Kingi, 2020).*

Year	Area (ha)
1840	29,880,000
1852	15,300,000
1860	9,630,000
1891	4,985,000
1911	3,211,000
1920	2,154,000
1939	1,813,000
1975	1,350,000
1986	1,181,740
1996	1,515,071



Map 10: *Māori land holdings, 2000, represented by dark areas. Source: (Ministry for Culture and Heritage, 2021)*

Māori participation in the contemporary agricultural sector has changed the relationship Māori have with their land and the environment. Modern agriculture, by its very nature, exploits natural resources and damages the mauri of the ecosystem which is directly opposed to the principles of kaitiakitanga (Forster & Papatipu, 2012). At first, Māori were encouraged to abandon cultural beliefs by European settlers, then they were coerced by the colonial government with subsidies, discounted loans, and tax breaks, and found traditional means of farming and economic development closed before becoming active and willing participants in damaging the environment (Consedine, 2007; Forster & Papatipu, 2012; Harmsworth et al., 2002).

There is still resistance among some contemporary Māori farmers regarding the use of manure and some are wary of synthetic fertilisers, but in general, Māori use of fertiliser is a standard practice affected only by its cost to purchase and apply (Peters, 2006). Māori applied 52,300 tonnes of fertiliser and 9,100 tonnes of lime and dolomite to their land at an average of 8 tonnes per hectare in the 12 months leading up to the end of June 2019 (Statistics, 2016). The large application rate of fertiliser is a complete reversal of colonial-era Māori who were repulsed at the thought of applying manure (Wood, 2003). Quoting Colenso, Schaniel (2001, p.5) provides the following account about colonial-era Māori and their view of animal manure:

> *"One striking peculiarity, however, should not be omitted, in which too, I think, they differ from all agricultural races, their national nonusage of all and every kind of manure…But their whole inner-man revolted at such a thing; and when the early missionaries first used such substances in their kitchen garden it was brought against them as a charge of high opprobrium. And even in their own potato planting in after years they would not use anything of the kind, although they saw in the gardens of the missionaries the beneficial effects arising from the use of manure; and as the potato fresh ground every year…rather than to use the abominated manure."*

Further, an 1869 story in the Otago Daily Times regarding Rev. Richard Davis, a missionary in New Zealand for 39 years whose responsibilities included supervising all mission stations and agricultural activities, recounting the fact that the Māori labourers he employed to spread manure "were in concern for their souls" due to working with animal manure (Wood, 2003).

It is argued that there is very little difference between contemporary Māori and non-Māori agriculture and while this may be true concerning farming practices there is a distinctive difference in the way Māori view their relationship with the land (Peters, 2006). However, as evidenced by their willingness to participate in activities that are known to degrade the ecosystem, pollute the land, reduce soil biodiversity, and affect human health, Māori can also view their agricultural land through a flexible and pragmatic lens (Nielsen et al., 2015; Savci, 2012; Wall et al., 2015).

It can be argued that Māori participation in these activities is not entirely wilful or within their control. Government control over Māori land, agricultural practices, and features of the environment made it impossible for Māori to practice, teach, and learn kaitiakitanga, Forster (2012, p. 118) explains:

> *"Use of land in Māori title was restricted…and required hapū to discard customary values and practices related to the access and use of the ancestral landscape. Māori environmental knowledge, ways of knowing, and associated practice became fragmented and its development disrupted."*

The fragmented and disrupted nature of Māori environment knowledge and practice, particularly in an agricultural context, is evident in their disregard for aspects of tapu, the use of animal by-products and chemical fertilisers, and the abandonment of traditional agricultural and kaitiakitanga practices. The application of silicon-rich compounds will not return contemporary Māori to a full and appreciable knowledge and use of cultural principles, but it could help increase agricultural revenue and restore and protect their environment. The availability of Si-rich compounds makes it possible for Māori to reintroduce agricultural and kaitiakitanga practices that the loss of land made impossible. The use of rāhui to restore degraded and exhausted soil and the prescribed burning and use of wood-ash is no longer required to achieve the outcomes of these traditional practices. Silicon-rich compounds can rapidly restore degraded and exhausted soil thereby removing the need for rāhui in the form of land fallowing. Silicon-rich compounds can provide almost immediate levels of monosilicic acid in the soil thereby removing the need for prescribed fire and the use of wood ash.

The history of Māori agriculture can be described as different phases of overcoming difficulties and adapting to new circumstances. When the ancestors of Māori first arrived in Aotearoa from Polynesia they encountered climatic difficulties that required a significant adaptation of growing practices. With the arrival of Europeans, Māori again faced difficulties and were required to adapt to new technologies, new practices, and new crops in order to make a successful transition to agriculture and commercial enterprise. The New Zealand Wars, land confiscation, and law changes created significant difficulties and circumstances that required Māori to adapt to less and lower quality land, lack of access to markets, and destroyed infrastructure. Today, there is a need for all agriculturalists, not just Māori, to adapt their practices to the ecological issues that are affecting Aotearoa-New Zealand, including the leaching of fertiliser nutrients into natural waters. Māori have demonstrated over the course of hundreds of years the ability to adapt successfully to even the most difficult circumstances. By utilising traditional understanding and combining it with current understanding to form a new hybrid practice, Māori can not only achieve their aspirations and protect and restore the mauri of Papatūānuku by reducing the leaching of nutrients and increasing water quality, but they can also lead the way for all Aotearoa-New Zealand farmers.

2.6 SILICON

> *"The biochemistry of silicon in plants is a riddle, wrapped in a mystery inside an enigma."*
> *– Emanuel Epstein*

2.6.1 Silicon in Nature

The name silicon (Si) is derived from the Latin word silex or silicis, which means flint or hard stone (Voronkov, 2009). In 1787 Antoine Lavoisier suspected that Si was an oxide element but there were no methods that allowed the element to be isolated. Sir Humphry Davy attempted to isolate Si in 1808 and also proposed the name silicium for Si by taking the Latin word silex and adding "ium" because he believed that Si was a metal (Baker, 2018). Silicon was first isolated by Joseph Louis Gay-Lussac and Louis Jacques Thenard in 1811 but neither man recognized it as a chemical element. It was not until 1823 that the Swedish chemist Jons Jacob Berzelius was able to isolate Si and gave the element the name silicium, the name first proposed by Davy in 1808, because he also believed Si was a metal rather than a metalloid (Figurovsky, 1970; Jaroniec, 2009; Voronkov, 2009).

Elemental Si does not occur naturally and is usually combined with oxygen to form the range of silicates that are found primarily in oxidative forms (Matichenkov et al., 2019). The most common form of Si is the oxide of Si known as silica (SiO_2).

Silica is formed by a reaction between Si molecules and the two atoms of oxygen; silicon (Si) + oxygen (O_2) = SiO_2. The reaction between Si and oxygen results in the formation of two forms of monosilicic acid, they being orthosilic acid (H4SiO4) and metasilic acid (H_2SiO_3). Orthosilic acid is the most common form of monosilicic acid and is found in soil and aqueous systems (Dietzel, 2002; Iler, 1979). Metasilic acid has never been isolated and is considered a hypothetical compound that may be found in sodium silicate solutions and is referred to as metasilic acid because it contains the metasilicate anion which occurs widely in nature (Bechtold, 1955; Jia-Wen et al., 2013; Jurkić et al., 2013; Mondal et al., 2009). Although orthosilic and metasilic acids are different forms of monosilicic acid it is common for both to be referred to as monosilicic acid (Dietzel, 2002; Iler, 1979; Jurkić et al., 2013; Mullin & Riley, 1955). Another soluble form of Si is polysilicic acid which forms during the condensation of monosilicic acid (Iler, 1979).

Silicon is the second most abundant element in the earth's crust after oxygen. Over 90% of the earth's crust is composed of silicate materials (Struyf et al., 2009). The largest volume of silicate material is found in the continental layer of the earth's crust but the highest concentration in the earth's crust is found in soil where clay soil concentrations are 40-70% and sandy soil concentrations are 90-98% (Bocharnikova & Matichenkov, 2010; Kovda, 1973). The majority of silicate materials in the soil are crystalline, amorphous Si dioxide, and aluminosilicates, with quartz being the most abundant. These same silicate materials constitute three-quarters of the earth’s lithosphere, and every sixth element in it is Si (Voronkov, 2009).

In its dissolved form silicate materials are found in all the water reservoirs of the planet. The earth’s atmosphere also contains silicate materials. Si compounds are found in the composition of all living organisms and were necessary for the appearance of life on the earth (Voronkov, 2009).

The geochemical classification of Si finds it being defined as both a mobile element and an inert element which is determined by the chemical properties of Si that make it possible to form either biogeochemically active substances such as amorphous Si dioxide, or inert mineralogical structures such as quartz (Matychenkov et al., 2016). Active forms of Si are composed of monosilicic acid, polysilicic acid, soluble Si substances, organosilicon compounds, and soluble complexes consisting of organic and inorganic compounds. Of the amorphous forms of Si, the biogenic form is one of the most soluble Si substances in the soil, and it controls the concentration of monosilicic acid in the soil solution. Biogenic forms of amorphous Si are found as phytoliths in plant tissue and the remains of decayed plants. Phytoliths can comprise up to 12% of the soil mass (Bobrova, 1995). Phytoliths remain in composted plant matter and survive the burning of plants or wood and remain rich with amorphous silica (Rajendiran et al., 2012; Shillito, 2018),

Silicon has the atomic number 14 and is the second element in Group 14 of Mendeleev's Periodic Table and sits directly below carbon due to their similar properties (Matichenkov et al., 2019). The basic chemical properties of Si are presented in Table 6.

Table 6: The basic chemical properties of Si.

Melting point	1410oC
Boiling point	2355oC
Density	2329 kg m−3 (at 0oC)(Iler, 1979) 2525 kg m−3 (liquid at mp)
Atomic radius	1.17 Å
Covalent radius	1.17 Å
van der Waals radius	2.00 Å
ΔHfusion	39.6 kJ mol−1
ΔHvap	383.3 kJ mol−1
Thermal conductivity	148 W m−1 K−1 (at 27oC)
Electrical resistivity	0.001 m (at 0oC)
Mass magnetic susceptibility	−1.8 × 10−9 kg−1 m3
Electronic configuration	1s22s22p63s23p2
Electron affinity	133.6 kJ mol−1
Ionization energies (kJ mol−1)	
M M+	786.5
M+ → M2+	1577.1
M2+ → M3+	3231.4
M3+ → M4+	4355.5
M4+ → M5+	16091
Stable isotopes (mass and natural abundance)	

28Si	27.9 92.2%
29Si	28.9 4.6%
30Si	29.9 3.1%

2.6.2 Monosilicic and Polysilicic Acids

Monosilicic acid plays an important role in the soil-plant system (Matichenkov et al., 2019). The amount of monosilicic acid in the soil is directly related to the amount of amorphous silica that is in the soil. In the root-dense upper soil zone, amorphous silica is found as different phytoliths and the volume of phytoliths is determined by the type and density of vegetation that has grown on the surface of the soil. Of the total amount of monosilicic acid that is in the soil, 95-99% is in a readily absorbed state with only the remainder being in true soil solution (Matychenkov et al., 2016). Monosilicic acid is plant-available and as such can be absorbed by plants (Pati et al., 2016).

Unlike monosilicic acids, polysilicic acids are chemically inert. Polysilicic acids play an essential role in the formation of soil properties including the linking together of soil particles by sorbing on them and forming siloxane bridges between the particles (Matychenkov et al., 2016). Like monosilicic acid, the amount of polysilicic acid in the soil is largely related to the amount of amorphous silica that is in the soil. Polysilicic acid is not plant-available and as such cannot be absorbed by plants (Pati et al., 2016). Being comprised of a chemically active component (monosilicic acid) and an inert but physically active component (polysilicic acid), active Si has a double effect on the soil-plant system. First, active Si increases the plant's protective properties against both biotic and abiotic stress including disease, insect attack, climatic conditions, salt, heavy metal, and hydrocarbon toxicity, and improves plant growth and crop yield (Bocharnikova & Matichenkov, 2010). Second, active Si optimises soil fertility including improved water holding capacity, improved physical and chemical soil properties, and maintains nutrients in plant-available forms (Bocharnikova & Matichenkov, 2010).

2.6.3 Silicon and First Human Use

The first use of Si materials has been dated to around 3.3 million years ago when stone tools were used in Kenya before any known species of the Homo genus existed (MacCarald, 2018). During the prehistoric era, approximately 2.5 million years ago, Homo habilis used a microcrystalline form of quartz, commonly referred to as flint, to make tools and weapons (Haviland et al., 2015; Verri et al., 2004). As early as 26,000 years ago the transformation of clays began with the firing of small figurines and shapes. Pottery was being made in China 18,000 years ago. Ancient Egyptians and Phoenicians turned sand into glass and the Romans made glass shapes such as bottles, vases, and containers (MacCarald, 2018). The indigenous peoples of America were using flint to make arrowheads 8,000 years ago, and 3,000 years ago Si dioxide was used in the manufacturing of gas (MacCarald, 2018; Matichenkov et al., 2019). Wood-ash has been used as a fertilizer since Neolithic times as did the first Polynesians to arrive in Aotearoa in about 1250 AD (Asare et al., 2021; Burtenshaw, 2010; Patrick, 2010). Materials that can be classified as Si-based have been used in agriculture from the 1st Century in Asia and the middle-ages in Europe (Datnoff et al., 1997; Liang et al., 2015).

2.6.4 Silicon in Agriculture

The use of Si, as Si fertiliser, in agriculture has demonstrated its ability to significantly enhance a plant's resistance to diseases and pests and increase soil fertility thereby contributing to higher production, lower input costs, and reduced negative impacts on environmental health (Liang et al., 2015).

Numerous laboratory, greenhouse, and field experiments have shown the yield increasing benefits of Si including a 10 to 30% increase for barley (*Hordeum vulgare L.*), 15 to 35% for corn (*Zea mays L.*), 15 to 80% for citrus (*Citrus spp.*), 10 to 40% for cucumber (*Cucumis sativus L.*), 15 to 100% for rice (*Oryza sative L.*), 20 to 30% for strawberry (*Fragaria spp.*), 10 to 50% for sugarcane (*Saccharum officinarum*), 15 to 50% for tomato (*Lycopersicon esculentum Mill.*), 15 to 35% for wheat (*Triticum aestivum L.*), and importantly for pastoralists a 10 to 25% increase in grasses and up to 22% in hay (*Stenotaphrum secundatum Kuntze, Cynodon dactulon L, Lolium multiform L.*) (Bocharnikova & Matichenkov, 2010; Korndörfer & Lepsch, 2001; Liang et al., 2015; Matichenkov & Campbell, 2010).

The first recorded scientific research activity into the use of Si-rich compounds in agriculture started in the early 1800s. The earliest documented research is believed to be on the concentration of Si in different species of plants (Liang et al., 2015). Between 1802 and 1812 Sir Humphrey Davy researched the role of Si in plant growth and its role in protecting the plant against biotic stresses. Davy recorded his findings in the book The elements of agricultural chemistry (Davy, 1846). In 1840, Justus von Liebig, the father of the fertiliser industry, published his book Chemistry in its application to agriculture and plant physiology which declared that in addition to N, P, and potassium (K) it was necessary to provide plants with Si nutrition to achieve sustainable and high yielding crop production (von Liebig & Playfair, 1843).

Since the initial breakthrough in the 1880s concerning its use in agriculture, a significant body of research and understanding of Si's role and function in the soil-plant system has been established. In modern times many scientists have made huge strides in demonstrating the validity of von Liebig's claim of Si's role in helping facilitate sustainable and high-yielding crop production and affirming the importance of Si in agriculture. Modern pioneers and luminaries in this area were Derek Birchall and his research into the biological role of Si (Birchall, 1995), Mihail Voronkov and his research into the active compounds of Si (Voronkov & Lukevics, 1969), Edith Carlisle and her research into the nutritional essentiality of Si for birds (Carlisle, 1982), and Ralph Iler and his work on the chemistry of Si (Iler, 1979).

The modern pioneers were followed by another generation of researchers whose insights and findings have led to a greater appreciation for Si and its practical application in agriculture for increased crop yield and crop quality. These scientists include Jian Feng Ma and his extensive work on the role of Si in plants (Ma, 2007), Eiichi Takahashi who discovered Si's transporter gene (Takahashi et al., 1990), Emanuel Epstein and his research into the biological function of Si and its quasi-essentiality to plants (Epstein, 2009), Yongchao Lian and his work on the stress functions of Si in plants (Liang et al., 2007), Hank-Maarten Laane and his work on the practical use of Si in agriculture (Laane, 2017), George Snyder and his work on the benefits of Si in agriculture and his organisation of an Si agricultural society, and Vladimir Matichenkov whose extensive work on Si in the soil-plant system led to a detailed understanding of the stress mechanism of Si in plants (Matichenkov et al., 2018).

A large body of work that is comprised of tens of thousands of published studies detailing tens of thousands of experiments and trials, conducted over many decades in almost every country in the world, has shown the ability of Si to increase crop yield, reduce plant disease, improve soil fertility, and increase the protective capability of plants against drought, salt, insects, and pests (Laing et al., 2006; Meena et al., 2014; Pozza et al., 2015; Rizwan et al., 2015; Snyder et al., 2016). However, the use of Si in agriculture is not a mainstream practice and its significance is largely unappreciated and misunderstood (Farooq & Dietz, 2015; Khomiakov et al., 2020). While a section on Si has been included in some university textbooks (Barker & Pilbeam, 2015) it is not included in the "Guide for Using Fertilizers and Optimizing Plant Nutrition 2017" published by the International Institute of Plant Nutrition (Khomiakov et al., 2020).

Some of the misunderstandings are due to Si not being officially recognised as an essential macronutrient for plant growth (Epstein, 2009). The accepted recognition for essentiality is based on the criteria as set out by Arnon and Stout (1934, pg. 371):

> *"(a) a deficiency of it makes it impossible for the plant to complete the vegetative or reproductive stage of its life cycle; (b) such deficiency is specific to the element in question, and can be prevented or corrected only by supplying this element, and (c) the element is directly involved in the nutrition of the plant quite apart from its possible effects in correcting some unfavourable microbiological or chemical condition of the soil or other culture medium."*

Nitrogen, P, and K are recognised as the three essential macronutrients (Barker & Pilbeam, 2015). Silicon's exclusion despite significant real-world evidence has been explained as being due to the analytical methodologies used to determine essentiality being developed and becoming the standard before the evidence of Si's potential essentiality could be confirmed (Epstein, 2009). The methodologies that were used to test for essentiality included growing plants to maturity in laboratory conditions using nutrient solutions that did not contain Si, thus showing that Si was not needed to complete the life cycle of the plant. Epstein (2009, p. 1) explains the flaw in this methodology when trying to establish the essentiality of Si:

> *"...the world's plants do not grow in the benign environment of the solution culture in plant biological research establishment. They grow in the field, under conditions that are often anything but benign. It is there, in the real world with its manifold stressful features, that the silicon status of plants can make a huge difference in their performance".*

The manifold stress features of Si, that make such a huge difference to plants, is its ability to protect the plant from biotic and abiotic stress (Epstein, 2009). Hundreds of substantial research reports have confirmed the role of Si in protecting plants from biotic and abiotic stress (Thakral et al., 2021). Abiotic stresses include drought and flooding, high and low temperature, nutrient deficiency, nutrient excess, heavy metal toxicity, aluminium (Al) toxicity, salt stress, and radiation. Biotic stresses include bacterial disease, fungal disease, nematode infection, insect attack, and pest incidence (Bhatt & Sharma, 2018; Ma, 2004; Ranjan et al., 2021; Thakral et al., 2021). The ability of Si to alleviate abiotic stress, including extreme climatic conditions, makes Si an important feature of cropping and pasture systems in the world's current climate-change environment (Thakral et al., 2021). A summary of the diseases, pests and stresses that Si has been shown to alleviate is provided in Table 7.

It has been argued that the exclusion of Si from essential status is partially due to a flawed definition of essentiality which overrides the evidence and facts that research has provided (Epstein, 1999). The large amount of physiological and biological evidence that shows Si is a significant factor in plant life has led some scientists to categorise Si as a quasi-essential element (Datnoff & Rodrigues, 2015; Epstein, 2009). While the essential status of Si can still be argued, its official classification as non-essential but beneficial to plants seems to be settled (Heckman, 2013). Likewise, any argument over Si's role in the alleviation of abiotic and biotic stress in plants is also settled (Thakral et al., 2021).

Table 7. *Biotic and abiotic stress in plants alleviated by Si. Source (Brahma, et al., 2020; Debona, et al., 2017; Song, et al., 2021).*

Biotic Stress		**Abiotic Stress**
Disease	Pest	Stress
Anthracnose	African striped rice stem borer	Aluminium toxicity
Angular leaf spot	Asiatic rice borer	Cadmium toxicity
Bacterial fruit blotch	Brown plant hopper	Chemical stress
Bacterial speck	Central shoot fly	Drought
Bacterial wilt	Chewing African armyworm	Heat
Basal stem rot	Fall armyworm	Iron toxicity
Blast	Greenbug	Lodging
Brown rust	Green leafhopper	Cold
Brown spot	Green peach aphid	Manganese toxicity
Diatraeasaccharalis	Green rice caterpillar	Radiation
Dollar spot	Hessian fly	Salinity
Downy mildew	Leaf folder	UV-B radiation
Early blight	Piercing-sucking Aphid	Water logging
Euschistusheros	Pink stalk borer	
Fusarium crown	Small brown plant hopper	
Fusarium patch	Spider mite	
Fusarium wilt	Stalk borer	
Gray leaf spot	Sugarcane borer	
Leaf streak	Sunflower caterpillar	
Pink rot disease	Weevil	
Powdery mildew	White-backed plant hopper	
Root rot	Whitefly	
Sheath blight	Yellow rice borer	

Silicon has been found to play an important role in providing beneficial effects in plant growth that lead to an increase in the growth, biomass, and yield of crops, particularly in plants that are under stressful environments (Etesami & Jeong, 2018; Liang et al., 2015). All agricultural crops are subjected to natural conditions that are hostile to plants and cause plant stress that can reduce plant growth and economic returns (Debona et al., 2017). Something as simple and as ubiquitous to Aotearoa-New

Zealand as wind is a stress to plants that can significantly reduce its growth and have major economic consequences for a farmer (Gardiner et al., 2016). Wind, drought, waterlogging, heat, cold, salinity, soil toxicity, and ultraviolet radiation are some abiotic stresses that can reduce agricultural crop productivity (Gull et al., 2019). Viruses, fungi, bacteria, nematodes, insects, and weeds are some biotic stresses that agricultural plants are subjected to and can cause crop yield loss (Gull et al., 2019). Plants are continuously exposed to a range of stresses and can be subjected to two or more stresses simultaneously (Gull et al., 2019). Further, one type of stress can cause another stress to be introduced such as when biotic stress weakens a plant thereby increasing its susceptibility to pathogens (Gull et al., 2019). Silicon has been shown to counteract both abiotic and biotic stresses in plants. One of the most important stress features of Si is its ability to reduce the intensities of seed borne, soil borne, and foliar diseases in economically important crops (Debona et al., 2017). Figure 12 illustrates various stress mechanisms and features of Si.

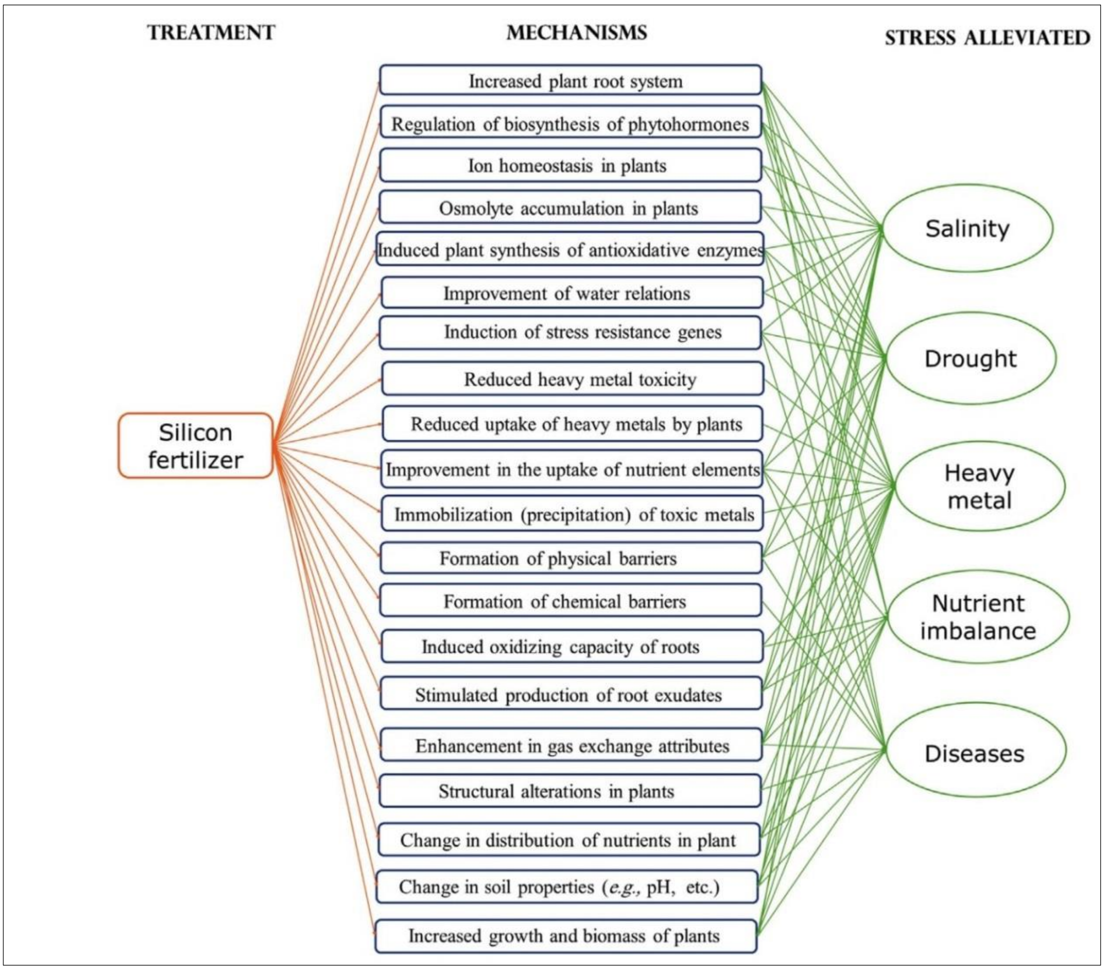


Figure 12: *Stress mechanisms and alleviation of Si fertilisers. Source: (Etesami & Jeong, 2018)*

Yield increases are primarily attributed to the direct effects of the stress features, optimisation of soil fertility, and the regulation of plant nutrient uptake, including N and P, that Si facilitates (Tripathi et al., 2014; Yavaş & Aydın, 2017). Yield increases can also be secondarily attributed to some indirect effects of Si such as an increase in microbial activity which in turn leads to an increase in the fixation of N from the atmosphere making more plant-available N available to the plant at no extra cost to the farmer (Bocharnikova & Matichenkov, 2010).

2.6.5 Silicon and Aluminium

Soluble Al is toxic to plants, is one of the major abiotic stress problems in agriculture, and can significantly hinder the growth and production of crops (Rahman & Upadhyaya, 2021; Silva, 2012). Soluble Al can also transfer P into a plant unavailable form which can lead to a plant P deficiency and a reduction in crop growth (Zheng, 2010). Applying Calcium Carbonate (CaCO3), also known as lime, is generally considered to be the most effective method that farmers can use to counter the effects of Al toxicity and reduce soil acidity. Because lime is alkaline it can counteract the acidity, raise soil pH and reduce Al toxicity which is the basis for the position that lime is effective (Li et al., 2019; Morton & Moir, 2018). However, lime can also transfer P into a plant unavailable form, is not always effective at combatting Al in the rhizosphere zone, and can increase the leaching of micronutrients (Hinsinger et al., 2006; Matichenkov et al., 2002). Lime can also intensify the loss of N through leaching (Røsberg et al., 2006). Despite the limitation of lime, the cost of its purchase and application, and the potential loss in productivity and therefore revenue, farmers are not given any alternative and are encouraged to apply lime annually (Hendry, 2016). The annual application of lime is evidence of its lack of effect, that despite its use soil acidity invariably increases, and Al toxicity returns.

Monosilicic acid is capable of reacting with Al and is more effective at reducing Al toxicity in acid soils than lime (Bocharnikova & Matichenkov, 2010). While lime has a single mechanism for reducing Al toxicity, five mechanisms have been identified for monosilicic acid, they being 1) monosilicic acids ability to increase soil pH, which is the same mechanism as lime, 2) monosilicic acids can be adsorbed by Al hydroxides which impairs their mobility, 3) monosilicic acid forms minutely soluble substances with the ions of Al, 4) mobile Al can be adsorbed by the silica surface, 5) Si can increase the plant's tolerance toward Al toxicity. All these mechanisms can work simultaneously with any single or dual mechanisms prevailing (Bocharnikova & Matichenkov, 2010).

Unlike the reaction between lime and P, the reaction between Si and P does not transfer P into a plant-unavailable form. The reaction between P and Si involves the absorption of P, which is kept in a plant-available form, and an increase in plant-available P through the transference of plant unavailable P (slightly soluble P) into an available form. The outcome of the use of Si to control Al toxicity is summarised by Liang (2015, p. 64),”...the recent experiments on acid soils showed that supply of different Si sources increased readily available P fraction followed by decreasing of Al- and Fe- bound fractions in wheat rhizosphere”.

2.6.6 Silicon and Fertiliser Reduction

Silicon is involved in a large number of biogeochemical reactions within the soil-plant and microbial systems including the mobility of N and P (Matichenkov & Bocharnikova, 1994). Several of these reactions make it possible to reduce the application of N and P fertiliser without having a negative effect on the plant or crop yield (Matichenkov et al., 2005).

Even with P fertilisation, plant-available P in the soil can be low and even deficient. P fixation, or transference from a plant-available to an unavailable form, can occur through the binding or adsorption of P by Al, iron (Fe), or calcium (Ca) thus potentially creating a plant P deficiency (Kochian et al., 2004). Second, the high susceptibility of P to leaching removes plant-available P from the plant rhizosphere which in turn can lead to a plant P deficiency (Matichenkov et al., 2020). Silicon positively affects P in the soil in three ways that can alleviate P deficiency. First, Si reacts with the slightly soluble phosphates and transfers the P that is only minutely soluble into a plant-available form, thereby increasing the volume of plant-available P without the need to apply P fertiliser. Second, Si absorbs P, while keeping it in a plant-available form, and the adsorption significantly reduces the loss of P to leaching (Matichenkov et al., 2020). The absorption of P by Si also keeps the P from transferring into a plant-unavailable form by negating the ability of Al, Fe, and Ca to bind or adsorb P (Kochian et al., 2004). These reactions between Si and P have shown the ability to optimise P plant nutrition even without the application of P fertiliser, by reacting with the P already in the soil (Bocharnikova & Matichenkov, 2010). When P fertiliser is needed the application rate can be reduced by 25-50% without having a negative effect on the plant or crop yield (Bocharnikova & Matichenkov, 2010).

Nitrogen is the most widely used fertiliser in the world with an annual application of approximately 90 million metric tonnes. However, the crop uptake of N rarely exceeds 40% of the total amount that is applied which indicates that there is a significant inefficiency concerning crop uptake of applied N fertiliser (Malav Jugal & Ramani, 2017). The efficiency of N use by crop plants increases significantly when Si is applied. Not only does Si regulate the uptake and mobility of N in the plant, but it also maintains an optimal level of N in the plant thereby dramatically increasing N use efficiency (Malav Jugal & Ramani, 2017; Neu et al., 2017). Nitrogen use efficiency, agronomic efficiency, physiological efficiency, and N recovery have all been shown to be higher with a combined application of N and Si than just N applied by itself at the same and increased rates (Malav Jugal & Ramani, 2017; Mohanty et al., 2020). Silicon promotes the fixation of atmospheric N by soil microorganisms by increasing microbial activity which in addition to an increase in N fertiliser efficiency further reduces the required application rate of N fertiliser (Bocharnikova & Matichenkov, 2010). It has been demonstrated in multiple crops that the application of N fertilisers can be reduced by 40% without a negative impact on the plant or crop yield (Galindo et al., 2021).

2.6.7 Silicon and Māori

Early Māori used Si-rich compounds for food production and maintenance tools such as adzes (Moore & Trotter, 2017; Phillipps et al., 2016). The burning of vegetation, including trees, and the spreading of wood ash, plant matter, and mulch for crop growing purposes was probably the most widespread form of Si use among Māori. While there does not seem to be any evidence that Māori were aware of the monosilicic acid contained in plant phytoliths, they were acutely aware of the fertilising benefits of burnt and decaying vegetation (Burtenshaw, 2010; Hargreaves, 1963).

Early European settlers of Aotearoa were baffled by many of the growing practices regularly used by Māori (Best, 1930; Hargreaves, 1959). Māori did not irrigate their crops and refused to use manure or any animal by-products as a fertiliser or soil amendment (Best, 1930; Wood, 2003). In modern times, the ability of early Māori to grow tropical crops in the temperate climate of Aotearoa has been identified as a demonstration of Māori crop growing skill (Roskruge, 2009). The crop growing practices that seemed counterproductive to early Europeans and a demonstration of growing skill by modern scientific standards were almost certainly enhanced by the application of phytoliths contained in wood ash and plant matter. Monosilicic acid, which is found in phytoliths, has been demonstrated to reduce the need for irrigation, increase the plant availability of nutrients, and protect plants from colder climates (Ma, 2004; Matichenkov et al., 2005). Māori may not have understood the mechanisms of Si that aided in their growing practices but through observation, they experienced the outcomes and understood its importance. It was only 200 years ago that observation led scientists such as Davy and von Liebig to discover just some of the mechanisms of Si. Even today with all the benefits and advancements of modern science many of the Si mechanisms that produce positive outcomes in agriculture are not fully understood (Bocharnikova & Matichenkov, 2010).

2.7 NUTRIENT LEACHING

2.7.1 Eutrophication

Eutrophication describes several natural processes, involving both terrestrial and aquatic ecosystems, that occur in response to the introduction and presence of excess nutrients (Gold & Sims, 2005). Eutrophication defines the nutrient status or the level of nutrients in an ecosystem. The ‘trophic’ or ‘nutrition level’ is used to classify the nutrient content of ecosystems including water bodies. Low nutrient level water bodies are classified as ‘oligotrophic’, intermediate level as ‘mesotrophic’, high level as ‘eutrophic’, and extremely high as ‘hypereutrophic’ (Gold & Sims, 2005).

The nutrient status of a water body is not constant and can increase or decrease due to natural and manmade processes. Eutrophication can happen naturally over long periods but if the nutrient levels increase at an accelerated rate due to human activities this process is referred to as 'anthropogenic eutrophication' (Khan & Mohammad, 2014). Anthropogenic activities are the root cause of the eutrophication of water bodies with excess nutrients coming from sewage, industrial waste, construction sites, urban areas, and agricultural practices. Excess nutrients come from two sources, point sources such as sewage and industrial waste, and nonpoint sources such as leaching and runoff from organic and inorganic fertilisers (Khan & Mohammad, 2014). Nonpoint sources of nutrients are the leading drivers of eutrophication and of the nonpoint sources, the leaching of fertiliser is a significant driver of eutrophication (Khan & Mohammad, 2014; Withers et al., 2014). Nutrient losses from agricultural land are difficult to quantify due to their diffuse nature and because their volume, form, and timing are variable due to short-term unpredictable changes in farming practices and hydrological conditions (Lennox et al., 1997; Matichenkov et al., 2005).

The leaching of nutrients into water can transform them from an oligotrophic state to a more nutrient-rich state including eutrophic and hypertrophic (Khan & Mohammad, 2014). Nutrients leached from agricultural land into natural waters can have a significantly negative effect on water quality (Matichenkov et al., 2020b). The leaching of nutrients into water bodies provides aquatic plant life with the N and P necessary to accelerate their growth which leads to an excessive amount of phytoplankton and algae. The excessive phytoplankton and algae lead to the deoxygenation of water, the death of aquatic life including fish, a reduction in biodiversity, and the formation of toxins from the decomposition of microbes and plants (Khan & Mohammad, 2014; Matichenkov et al., 2020b). Eutrophication is a root cause of toxic cyanobacterial blooms (Liu et al., 2019; Smith, 2003; Smith et al., 2016; Wang & Li, 2019). Cyanobacterial toxins are harmful to aquatic life and can pose a major risk to human health if the toxins are ingested (Wood & Dietrich, 2011).

Nitrogen and P are the greatest concern of all leached nutrients due to both of them being required to support aquatic plant growth and having been identified as the key limiting nutrients in aquatic ecosystems (Conley et al., 2009). It was during the

1970s that it became generally accepted that P was the primary limiting factor for aquatic plant growth and efforts to address eutrophication were based solely on the management of P (Sterner, 2008). However, it has been demonstrated that N is also a limiting factor and that any management system should adopt a management plan for P and N, particularly in New Zealand lakes (Abell et al., 2010; Sterner, 2008).

In principle, eutrophication can be reversed but it has been estimated that reversal could take over 1,000.0 years to recover from intensive fertilisation (Carpenter, 2005). A meta-analysis of 89 studies conducted around the world to examine the results of different eutrophication management strategies, determined that two-thirds of the sites reached and maintained recovery conditions (McCrackin, et al., 2017). Implied recovery times after the implementation of the eutrophication strategies ranged from less than a year to almost a century. The large variability in results reflects the complexity of all the factors that affect eutrophication and recovery (McCrackin, et al., 2017). The meta-analysis identified the reduction of nutrient inputs as being necessary to address eutrophication and while progress has been made in reducing point sources of nutrients more needs to be done with nonpoint sources, particularly from agriculture (McCrackin, et al., 2017).

2.7.2 Leaching

As was the intention of the green revolution, modern agriculture feeds almost 7.0 billion people around the world (Wang & Li, 2019). The feeding of this vast number of people seemed impossible only four decades ago (Briney, 2010; Ehrlich, 1971). The ability to feed 7.0 billion people is attributed to a massive increase in agricultural production that was made possible by the advancements in crop genetics and an 8-fold increase In N fertiliser use and a 3-fold increase in P fertiliser use (Jones & Downing, 2009; Wang & Li, 2019). However, the increase in fertiliser use has at the same time seen a decrease in nutrient use efficiency (San Martín, 2017).

Nutrient leaching is the process of dissolved nutrients being moved away from the rooting zone of plants. Some nutrient leaching occurs naturally within the environment, but agricultural activities can increase nutrient losses significantly (Lehmann & Schroth, 2003). In general, the nutrients are transported away from the rooting zone by rain or irrigation water, when the amount of nutrient in the soil exceeds the soil's absorption capacity or the nutrient uptake capability of the crop (Lehmann & Schroth, 2003). Soil is a porous medium that is comprised of a highly complex system that affects the way water and nutrients are transported. Due to this complexity, water and nutrients do not flow through the soil in a uniform or isotropic way; instead, the transportation can be disorderly, rapid, and far-reaching including reaching natural water (Clothier & Green, 2005; Matichenkov et al., 2005).

Nitrogen and P nutrients go through a series of physical, chemical, and biological processes in the soil which solubilise and make them available for plant uptake. These processes also increase the mobility of nutrients in the soil which in turn makes the nutrients vulnerable to leaching (Rashmi et al., 2017). Nutrient leaching and the volume of leaching is regulated by several factors including soil type, climatic conditions, nutrient content, amount and intensity of rainfall or irrigation, the type of crop plant, the extent of the soil surface covered with crop plants, physical and chemical soil properties, and crop management practices (Ghiberto et al., 2015; Rashmi et al., 2017; Wang et al., 2014). With fertiliser application having increased and the uptake of nutrients by plants decreasing, an excess amount of nutrient is left in the soil and is vulnerable to leaching. The single biggest factor in the leaching of N and P fertiliser is the application of fertiliser to the soil in a volume that exceeds the crop's demand for and ability to uptake nutrients (Liu et al., 2019; Wang & Li, 2019). Depending on the state of these factors, leaching can be as high as 80.0% of the nutrients applied to the soil as fertiliser (Matichenkov et al., 2005).

2.7.3 Aotearoa-New Zealand Water Quality

Despite having one of the most dynamic economies in the OECD and its international reputation as a clean and green country, New Zealand is approaching its environmental limits with increasing greenhouse gas emissions, threats to biodiversity, and the pollution of its natural waters (OECD., 2017). New Zealand has 425,000.0 km of rivers and over 4,000.0 lakes. Approximately 13.0 million hectares, which represents 50.0% of the total land area of New Zealand, is used for primary production and is the predominant land use around stream, river, and lake catchments (Environment, 2007).

Up to 90.0% of New Zealand's total river length, which is located in pastoral areas, exceeds the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (Statistics, 2019).

The poor quality of New Zealand's natural waters, as seen in its high concentration of nutrients, excessive phytoplankton growth, and high level of microbial and industrial pollution, is a significant environmental problem (Gluckman, Cooper, et al., 2017). The poor quality is due largely to human activities including deforestation, draining wetlands, erection of dams and industrial facilities, and urbanisation. Fresh water quality has generally been getting worse and while some of the most degraded fresh water is in urban areas, the pollution of lakes, rivers, and streams is dominated by agricultural runoff (Salmon, 2019). One of the most important and significant impacts of agricultural pollution has been the rapid intensification of agriculture, including the increased use of fertilisers (Gluckman, Bardsley, et al., 2017). River quality trends for N had been worsening the central North Island, Gisborne, Taranaki, south-eastern South Island, Otago, Southland, and parts of Canterbury for the ten years between 2008 and 2017. Phosphorus had also been worsening in most of the North Island for the same period (Ministry for the Environment & Stats NZ, 2020).

Despite the problem being recognised for several decades and vast sums of money being spent on improving the treatment of city and industrial wastewaters, New Zealand's water quality has been declining for the last 25.0 years (Davies-Colley, 2013). While point source pollution, such as city and industrial wastewaters, can be treated and controlled, it is much more difficult to control nonpoint source pollution. The gains in water quality from point source improvements have been counteracted by the steady increase in nonpoint sources, particularly N and P leached from agricultural land. It will be a significant challenge to improve water quality with New Zealand's trend toward agricultural intensification (Davies-Colley, 2013).

2.7.4 Nutrient Leaching Strategies

On-farm nutrient leaching mitigation strategies have been researched, evaluated, and recommended in New Zealand for a considerable time. Riparian planting, stream fencing, irrigation management, fertiliser management, grazing management, cover crops, and constructed wetlands have all been utilised as mitigation strategies for over thirty years (Collins, 2011; De Klein, 2001; Di & Cameron, 2002; Saggar et al., 2005; Tanner & Kloosterman, 1997; Ward et al., 1985). However, despite the availability of these strategies, the overall national trend has been an increase in nutrient leaching (Roxborough, 2020; Snelder et al., 2021; Statistics, 2019).

Fresh water quality has generally been getting worse and while some of the most degraded fresh water is in urban areas, the pollution of lakes, rivers, and streams is dominated by agricultural runoff (Salmon, 2019). River quality trends for N had been worsening the central North Island, Gisborne, Taranaki, south-eastern South Island, Otago, Southland, and parts of Canterbury for the ten years between 2008 and 2017. Phosphorus had also been worsening in most of the North Island for the same period (Ministry for the Environment & Stats NZ, 2020).

One reason for the increase in nutrient leaching is the slow uptake of the mitigation strategies by farmers who often view the strategies such as riparian planting and the fencing-off of waterways, as having little benefit and not being cost-effective (Journeaux et al., 2014; McDowell, 2012; Ministry for the Environment, 2001a). The views held by these farmers have some selective merit. Research has shown that buffer strips, under some circumstances, can reduce P leaching by up to 20.0%. However, this result came at a significant cost to the farmer of $30.00 per kg of P (McDowell & Nash, 2012).

A further study evaluated the cost and effectiveness of restricted grazing and the use of nitrification inhibitors to reduce N leaching from dairy farms (Romera et al., 2017). Restricted grazing was found to have reduced N leaching by 23 – 32.0% but again at a significant cost to the farmer of $32.00 - $37.00 per kg of N. The use of nitrification inhibitors did not produce a statistically significant result despite the cost of a two-time per year application. A combination of restricted grazing and a nitrification inhibitor reduced N leaching by 31 – 40.0% at $40.00 per kg of N (Romera et al., 2017).

Urea costs approximately $950.00 per tonne or $0.95 per kg. Superphosphate costs approximately $339.00 per tonne or $0.33 per kg. Some leaching mitigation strategies can cost the farmer almost 100.0 times the amount of purchasing P and almost 40.0 times the amount of purchasing N.

A report prepared for the Ministry for the Environment provided a comprehensive list of nutrient mitigation strategies used in New Zealand (McDowell et al., 2013). Table 8 summarises 'Multiple Target' strategies and Table 9 summarises 'Single Target' strategies. 'Multiple Target' refers to a single strategy that targets a simultaneous reduction in both N and P leaching. 'Single Target' refers to a single strategy that targets N or P and not both simultaneously (McDowell et al., 2013).

Table 8: *Summary of multiple target nutrient leaching mitigation strategies. Source (McDowell et al., 2013)*.

Mitigation Strategy	N Effectiveness	Cost	P Effectiveness	Cost
Bridge Crossing	Low	Medium	No data	No data
Constructed Wetlands	Very High	High	Medium	Very High
Natural Wetlands	Very High	Very High	Low	Very High
Sediment Traps	No data	No data	Low	Very High
Stream Fencing	No data	No data	High	Low
Buffer Strips	No data	No data	High	High
Restricted Winter Grazing	n/a	No data	High	Medium
Off Pasture Confinement	High	Medium	Medium	Medium
Great Pond Storage	Medium	Medium	Medium	Low
Deferred Pond Storage	Medium	Medium	Medium	Low
Low Rate Pond Irrigation	Medium	High	High	Low
Enhanced Pond System	Very High	Very High	High	Very High

Table 9: *Summary of single target nutrient leaching mitigation strategies. (McDowell et al., 2013).*

Mitigation Strategy	N Effectiveness	Cost	P Effectiveness	Cost
Denitrification Beds	Very High	Very High		
Precision Agriculture	High	Low		
Animal Type	High	Medium		
Diuretic	Low	Low		
N Use Efficiency	Medium	Medium		
Nitrification Inhibitors	Medium	Medium		

Low N Feeds	Low	Low		
Low P Fertiliser Solubility			Medium	Low
Optimum P Soil Test			Low	Low
Sorbents			High	Very High
Tile Drain Amendments			Very High	Medium
Alum Use - Cropland			Medium	High
Alum Use - Pasture			Low	Very High
Red Mud Use - Land			Very High	Medium

The report discusses the cost and efficacy of each strategy in addition to its inherent drawbacks. The drawbacks are 1) the cost, 2) the length of time it takes to achieve water objectives, and 3) the potential for a strategy to worsen other environmental conditions (McDowell et al., 2013). The drawbacks identified in the report correspond with other research. Cost is identified as a general problem in achieving water quality objectives and the use of mitigation strategies may only be cost-effective if subsidies are available to farmers (Doole & Romera, 2014; Larsson et al., 2005). Riparian planting, or buffer strips, can take decades to achieve water quality objectives (Collins, 2011). Strategies that use alum or red mud, while ameliorating P leaching, can cause environmental problems such as soil acidification, Al toxicity, Na toxicity, and heavy metal toxicity (Dassanayake et al., 2015; Gruiz et al., 2012; Kim et al., 2002; Milačič et al., 2012).

Further, McDowell (2013) points out the unlikelihood of one strategy alone being able to meet a single water quality objective. This position also corresponds with other research. A whole-farm management system that uses multiple strategies must be implemented because any single strategy that reduces nutrient loss in one area of the farming system will likely be lost in another area if the whole farm is not managed for nutrient loss (Rotz, 2004). Similarly, when single and multiple strategies are compared for their ability to reduce the amount of nutrient leaching, the multiple strategy practice proves more effective (Howarth & Journeaux, 2016).

2.7.5 Silicon and Nutrient Leaching

There are many factors involved in the causes and volume of nutrient leaching including the physical and chemical properties of the soil (Ghiberto et al., 2015; Rashmi et al., 2017; Wang et al., 2014). Two of the biggest factors are the inability of the crop to take up all excess N and P and the inability of the soil to absorb all excess N and P (Lehmann & Schroth, 2003; Liu et al., 2019; Wang & Li, 2019). Silicon can react with the physical and chemical properties of the soil including N and P nutrients (Matichenkov & Bocharnikova, 2001). Research has demonstrated that Si can engage in multiple reactions simultaneously (EA Bocharnikova & VV Matichenkov, 2010a). Silicon can be described as a multiple target mitigation strategy but unlike the strategies described by McDowell (2013) the use of Si can result in multiple mechanisms simultaneously being, directly and indirectly, involved in reducing the leaching of N and P (EA Bocharnikova & VV Matichenkov, 2010a; Matichenkov & Bocharnikova, 2001; Matichenkov et al., 2005).

A hypothesis that an exchange between silicate ions and phosphate ions could occur due to Si fertilisation was first presented in 1906 (Hall & Morison, 1906). After further research, it was determined that Si-rich substances could increase the quantity of plant available phosphates and the formation of silicates through the exchange or displacement of the phosphate anion with the silicate anion (Gladkova, 1982; Matichenkov & Ammosova, 1996; O'Reilly & Sims, 1995). The occurrence involves an increase in the concentration of monosilicic acids in the soil solution and their adsorption of phosphates that were only minutely soluble wherein an exchange or the displacement of the phosphate-anion by the silicate anion took place. These reactions were followed by desorption of the phosphate–anion which leads to an increase in P in the soil solution and a new equilibrium between silicate and phosphate-anions (Matichenkov & Bocharnikova, 2001). In short, Si initiates two processes with P. 1) Transferring phosphates that are only minutely mobile into a mobile form. 2) The physical adsorption of mobile phosphates (Matichenkov et al., 2005)The increased amount of plant-available P in the soil solution reduces the required application of P fertiliser and consequently reduces excess P that is vulnerable to leaching. Phosphorus that is absorbed by Si is significantly less vulnerable to leaching (Matichenkov & Bocharnikova, 2001; Matichenkov et al., 2005).

Nitrogen, like P, can also be adsorbed by Si-rich minerals and substances and kept in a plant-available form and is an important feature of reducing N leaching. The application of Si-rich substances to the soil can enhance the root system of plants by up to 200.0% and significantly increase soil microbial activity, both of which can increase nutrient retention in the soil and enhance a plant's ability to increase its uptake of nutrients, thus reducing their leaching (Drinkwater et al., 2017; Ge et al., 2010). The increase in the plant uptake of N can be more than 50.0% and P by up to 104.0%, meaning there is less N and P in the soil that is vulnerable to leaching (Matichenkov, Bocharnikova et al. 2020). Importantly, an increase in the plant uptake of macronutrients can result in an increase in plant biomass which is an important economic consideration for the farmer (Matichenkov et al., 2020a).

Nutrient leaching is due in large part to the low retention of nutrients by the soil. This is particularly true for sandy soils which usually have a low nutrient retention capacity where 20.0 – 80.0% of nutrients applied as fertiliser can leach or runoff to ground and surface waters (Campbell et al., 1985; Sims et al., 1998). A soil's low nutrient retention capacity is typically due to two factors. 1) The soil is lacking in essential clays that contain aluminosilicates and metal-oxide in the soil’s E horizon. 2) The E horizon has a seasonal shallow water table which promotes lateral nutrient movement (Harris et al., 1996; Mansell et al., 1991). Therefore, a key factor for reducing nutrient leaching is to address the soil's adsorption capacity (Dassannayake, 1990; Matichenkov et al., 2005). Silicon rich substances can initiate the formation of secondary clay minerals in the soil which can improve the physical and chemical properties of soil including soil structure and nutrient adsorption capacity (E Bocharnikova & V Matichenkov, 2010b). An increase in monosilicic acid in the soil solution can contribute to an improvement in the soil's adsorption capacity throughout the soil profile. As monosilicic acid moves down through the soil profile it increases the adsorption capacity of soil including its deeper horizons and this effect increases and strengthens over time (Matichenkov et al., 2020a). The multiple mechanisms for the reduction of nutrient leaching that are inherent in Si can decrease N leaching by 25.0 –

60.0% and P leaching by 40.0 – 80.0% (Elena Bocharnikova & Vladimir Matichenkov, 2010; Matichenkov et al., 2005a)

The drawbacks of the mitigation strategies identified by McDowell (2013) are 1) the cost of each strategy to achieve water objectives, 2) the length of time it takes for the strategy to achieve water objectives, and 3) the potential for a strategy to worsen other environmental conditions. The use of Si fertilisers or Si-rich soil amendments as a leaching mitigation strategy can overcome all these drawbacks. Si-rich substances have a cost, however, they can replace lime for the control of pH and aluminium toxicity, reduce the need for macro and micronutrient fertilisers and soil amendments, and increase crop yield. The benefits of Si fertilisers can offset the cost of its use by a considerable margin (Alvarez & Datnoff, 2001; Matichenkov, 2019). The physical and chemical interactions that take place between Si and the soil, plant and microbial systems can commence very quickly after the application of Si fertilisers. Nutrient leaching reductions can be achieved within a single cropping season and water quality can begin to improve within the same timeframe (Matichenkov et al., 2005). Several Si fertilisers are available commercially and include chemical products, by-products of the steel and iron industries, and natural minerals (Liang et al., 2015c). Although all Si-rich compounds are effective at reducing nutrient leaching and providing additional agricultural benefits, not all of them are environmentally friendly (Liang et al., 2015c). Slag-based Si fertilisers may contain heavy metals and therefore they pose some potential environmental risks (Gascho, 2001). Other Si fertilisers are manufactured from naturally occurring silicate minerals and are cost-effective, agriculturally effective, and environmentally friendly (Etesami & Jeong, 2018; Liang et al., 2015c; Matichenkov, 2019; Ning et al., 2014).

CHAPTER 3

Materials and Methods

"...the world's plants do not grow in the benign environment of solution culture in plant biological research establishments. They grow in the field, under conditions that are often anything but benign. It is there, in the real world with its manifold stressful features, that the silicon status of plants can make a huge difference in their performance."

- Emanuel Epstein

3.1 Introduction

This study's research aimed to determine the ability of three selected Si-rich compounds to help Māori farmers meet the environmental, and economic aspirations they have for their land (Dewes et al., 2011). In order to meet that aim four pot trials that consisted of sixty-four pot tests, each with three replications, for a total of 192.0 tests, were conducted simultaneously over of period of 7.0-weeks each. The four pot trials examined the following:

1. Crop yield comparisons with and without Si-rich compounds
2. N and P leaching comparisons with and without Si-rich compounds
3. Crop yield comparisons with reduced application rates of N and P fertilisers, with and without Si-rich compounds
4. Comparison between lime with Si-rich compounds and their effects on:
    - Phosphorous fixation in the soil
    - Soil pH and Al toxicity

The pot trials were conducted in Hamilton, New Zealand on a private and fully enclosed block of land measuring 13.0 meters by 9.0 meters. The pots were placed on tables in three vertical rows of 64.0 horizontal rows. The vertical pot rows consisted of three replications of the same test and each horizontal row consisted of a different test. Figure 13 is a picture of the pot trial site and the configuration of the test posts.

Figure 13: *Pot trial site*

The pot trials were conducted outdoors in a natural environment in order to simulate real-world conditions as closely as possible including the plants being exposed to rain, wind, and cold temperatures. Natural conditions were used for the trials to avoid the benign controlled conditions of a laboratory or greenhouse where the stress features of Si may not be fully realised and lead to an imprecise understanding of the effects of Si (Epstein, 2009).

Pot trials in general are important for the investigation of a plants reaction to applied treatments and their interaction with other external factors (Hohmann et al., 2016). Environmental factors such as soil variability, which can cause fluctuations in field trials, can be controlled and limited with pot trials making them more repeatable and reproducible than field trials (Hohmann et al., 2016).

Pot trials are a rapid, inexpensive, and flexible method to obtain plant growing and soil property data. Pot trials are not as accurate or broadly applicable in the real world as field trials but they require less labour, time, resources, equipment, and farm machinery (Janssen, 1974). Pot trials are not as fast or as economic as laboratory trials at obtaining data, but they are more broadly applicable, and in that sense are more accurate, and they are more flexible (Hohmann et al., 2016, Janssen, 1974).

Flexibility is an important attribute for this study because pot trials are generally conducted in a controlled environment but this study's trials were not. Pot trials do not produce the same results as field conditions, primarily due to the shallow soil depth, low soil aeration, and the disturbance in natural soil structure. However, despite their limitations, pot trials still produce a statistically significant correlation coefficient with field conditions (Ogunkunle & Beckett, 1988). The pot trials for this study were conducted in an uncontrolled environment that was far more like real-world farming conditions than controlled in-door pot trials. The flexibility of pot trials made the uncontrolled approach possible but without the disadvantages of field trials. Uncontrolled outdoor pot trials have been found to be statistically significant and produce a higher correlation coefficient to field trials than controlled indoor pot trials (Ogunkunle & Beckett, 1988).

In addition to the pot trials, a column leaching experiment was also conducted which consisted of 10 tests, each with three replications, for a total of 30.0 tests that were conducted over a period of 24.0-hours. The column experiment examined the following:

1. Total N and Total P in the leachate
2. Total N, Total P, and Olsen P in the soil.

The column experiment examined environmental and economic aspects of farming that are directly relevant to the aims of this study and were discussed in the literature review. The column experiment was conducted in the same location as the pot trials but inside a double garage that had been converted into an office and work area that meets the criteria for a suitable laboratory workplace (Okalebo et al., 2002).

Column leaching experiments are an important tool in the interpretation of leaching phenomena (Chandler et al., 1997).A column test simulates the dynamic phenomenon of leaching and Is more representative of field conditions than alternate leaching tests such as batch testing (Townsend et al., 2003).

The primary testing component of the pot trials and column experiments is a comparison between traditional agricultural inputs and Si-rich compounds. There are several types of Si fertiliser are available on the market today:

1. Synthetic – these Si fertilisers, such as potassium silicate, are commonly found in liquid forms. This type of Si fertiliser is effective in activating the plant's defence system against biotic and abiotic stresses.
2. Plant-based remains – plant or wood ash and plant-based remains, as used in traditional Māori agriculture, can be a good source of Si. The efficiency and effectiveness of this type of Si depend on several factors including the volume and type of plant that is used.
3. Silicon-rich industrial by-products – calcium silicate slag is one of the most widely used Si fertilisers. However, these types of Si-rich products can contain heavy metals and pose environmental risks.

4. Natural Si-rich minerals – natural minerals such as zeolite, diatomaceous earth, and bentonite are generally friendly to the environment.

The selection of the Si-rich compounds that were used for this study was based on four criteria:

1. Market availability
2. Market price
3. The alignment of the Si-rich compound to the principles and values of kaitiakitanga
4. The concentration of plant-available Si in the compounds.

It was important for each of the selected compounds to have different concentrations of active Si because this would allow for the categorisation of a low rate, medium rate, and high rate of plant-available Si. Each rate of active Si would have a different cost, with the low rate being the less expensive and the high rate being the most expensive. Each rate of active Si would also produce different farming and environmental outcomes.

In general, synthetic Si-rich compounds have a high concentration of active Si and meet the selection criteria for this study. However, these compounds come in a liquid form and require application by fertigation. Reference to Figure 14 shows that except for the region of Canterbury, irrigating farmland is not a common practice in New Zealand. Therefore, fertigation would not fit within most current farming systems which makes the use of a liquid Si-rich compound a difficult and costly endeavour for the majority of farmers. Plant-based Si-rich compounds meet 3 of the 4 selection criteria. However, the concentration of plant-available Si in plant-based compounds is low and the extremely high application rate that is required to affect the outcomes required by large-scale agriculture would likely prove to be prohibitively expensive, labour intensive, and impractical. Industrial by-products that contain heavy metals do not align with the principles and values of kaitiakitanga thereby making products such as calcium-silicate slag untenable.

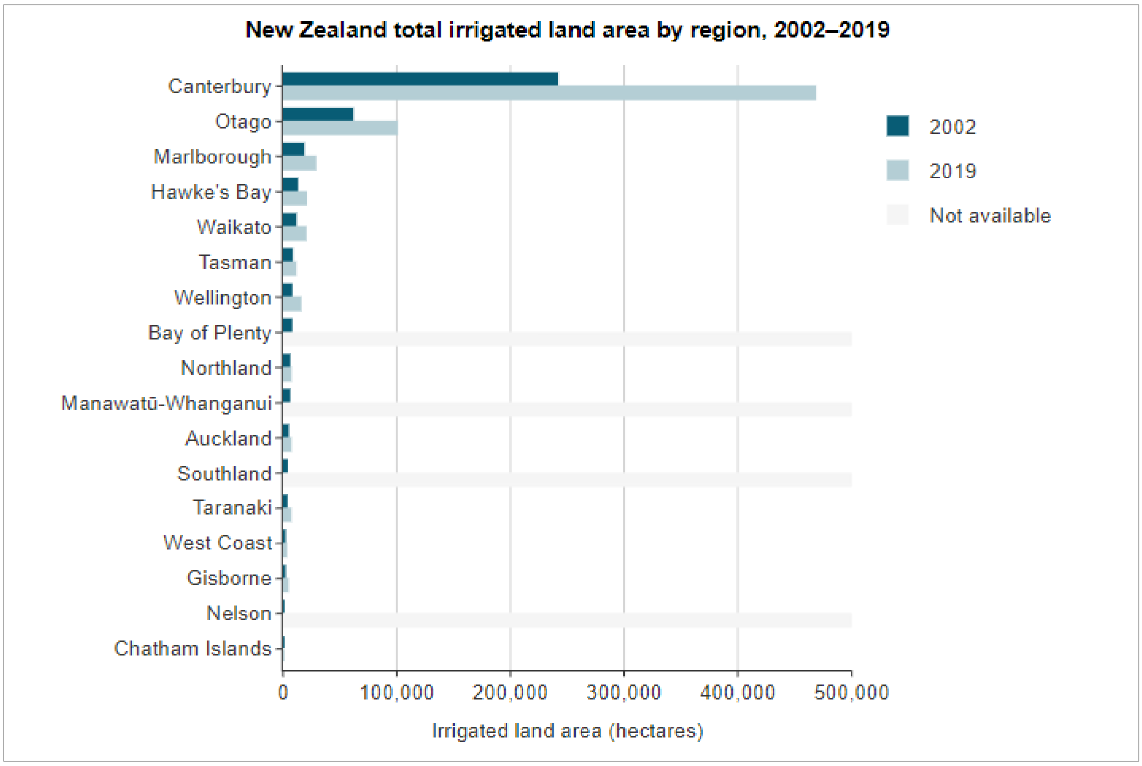


Figure 14: *Irrigated land area, New Zealand. Source: (Stats NZ, 2021b)*

Natural Si-rich minerals meet all the criteria for use in this study. However, some of the natural minerals can have a low level of plant-available Si which necessitates a high rate of application which in turn can make their use prohibitively expensive. It was therefore decided to combine a natural mineral with a synthetic compound and create an additional Si-rich compound. Combining the two compounds would increase the cost but the final product would have a higher concentration of active Si which in turn could prove to make the product cost-effective. Therefore, an analysis was conducted on all the natural Si-rich minerals to determine which one would be the most suitable to be mixed or "activated" with the synthetic compound. The selection of the natural mineral that was to be activated by the synthetic compound was based on three criteria:

1. Particle size
2. Surface area
3. Complexity of structure

Following the selection of the natural Si-rich compound and the creation of the additional "activated" compound, the solubility of each of the natural Si-rich minerals was analysed using a water and weak acid extraction (Bocharnikova et al., 2011).

Three different Si-rich compounds were selected for this study. They are referred to in this study as Compound-A, Compound-B, and Compound-C and each has a different concentration of active Si:

1. Compound-A, low concentration
2. Compound-B, medium concentration
3. Compound-C, high concentration

Compound-C is a mixture of Compound-B and a liquid Si fertiliser that contains 28.0% monosilicic acid. The liquid Si fertiliser was not used in this study by itself because it requires application by fertigation.

Brown soil of a loam texture was used in the trial because it is the most common agricultural soil in New Zealand (Hewitt & Dymond, 2013). A soil map of New Zealand illustrating this point is presented in Figure 15.

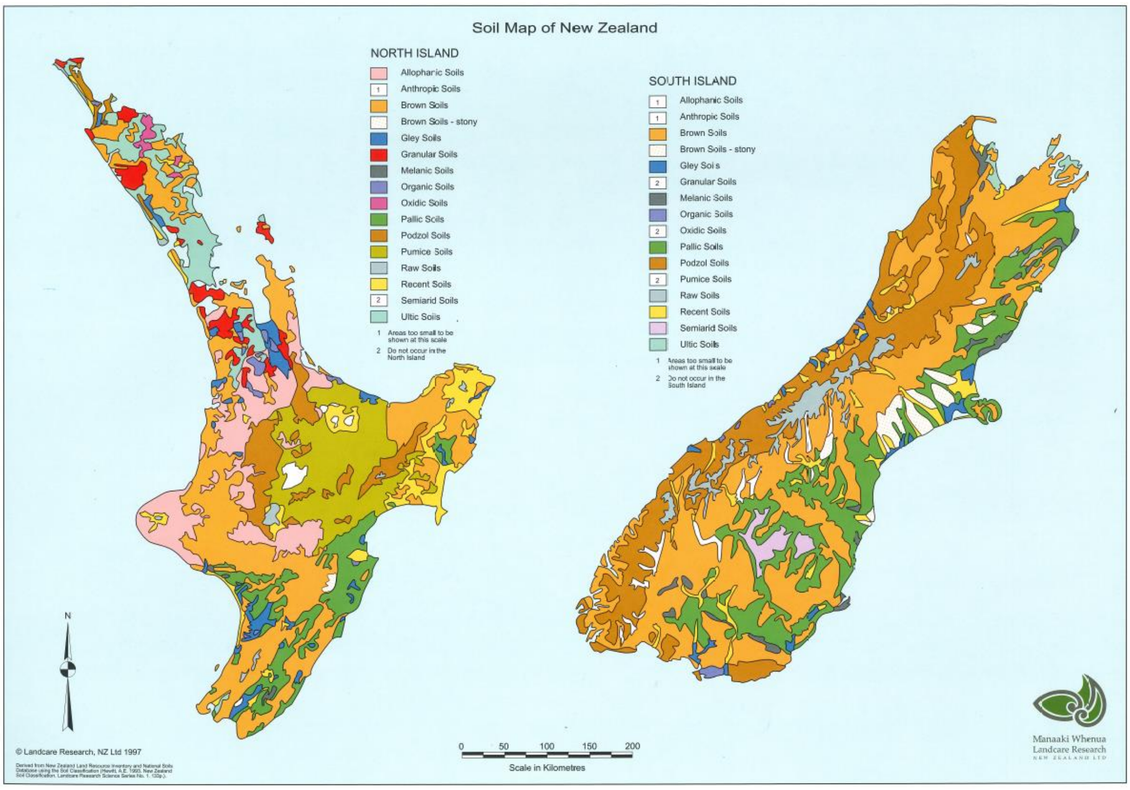


Figure 15: *Soil map of New Zealand. Source: (Landcare Research, 1997)*

3.2 MATERIALS

3.2.1 Silicon-Rich Minerals

The following natural Si-rich minerals were analysed to determine their particle size, surface area, and structure using a Scanning Electron Microscope (SEM).

1. Washed Quartz Sand – white granules
2. Chemically Pure SiO2 – white granules
3. Zeolite – 74.0% SiO2, dense light grey granules
4. Compound A – 73.0% SiO2, dark grey to black granules
5. Compound B – 68.0% SiO2, dense light grey to an off-white fine powder

The SEM analysis required the following materials:

1. JEOL, Scanning Electron Microscope (SEM).
2. JEOL, Auto Fine Coater, Model JFC-1600.

3.2.2 Compound-C

Following the results of the SEM analysis Compound-B was selected for activation. Compound-B was mixed with concentrated monosilicic acid at a ratio of 20:1 to form Compound-C.

1. Compound C – 88.0% SiO2, dense light grey to off-white fine powder

The following materials were used for the activation process:

1. Concentrated monosilicic acid – liquid, 28.0% Si
2. Distilled water
3. Sieves
4. Temperature controlled electric oven
5. Magnetic stirrer – Aldrich, Variomag MONO.

3.2.3 Natural Mineral Analysis

Following the creation of Compound-C, all the natural Si-rich minerals were tested for their concentration of active Si. The test involved water extraction and acid extraction with spectrophotometric analysis.

The water and acid extraction method and analysis required the following materials:

1. Polyethylene measuring containers
2. Distilled water
3. Filters
4. Falcone tubes
5. Centrifuge – Aldrich, Hettich EBA 21 with adapter for 6.0 50.0ml falcone tubes
6. Hydrochloric acid
7. Molybdate
8. Ascorbic acid
9. Spectrophotometer – Biochrom, Model Libra S12.

3.2.4 Trial and Experiment Soil

Topsoil was purchased from Complete Landscape Supplies in Hamilton, New Zealand for use in the pot trials and column leaching experiment. The basic properties of the trial soil are provided in Table 10.

Table 10: *Basic properties of the trial soil.*

	Measurement	**Level**
pH	pH units	5.7
Total Base Saturation	%	50
Total Nitrogen	%	0.3
Olsen Phosphorus	mg/L	17
Total Phosphorus	mg/kg	508
Aluminium	mg/kg	1.5
Total Aluminium	mg/kg	24,000
Potassium	me/100g	0.5
Calcium	me/100g	5.7
Magnesium	me/100g	0.9
Sodium	me/100g	0.3
CEC	me/100g	15

3.2.5 Trial and Experiment Inputs

Nitrogen, P, and lime inputs were used in the pot tests. An Al compound was also used in a set of pot tests:

1. Urea – Ravensdown Ltd, New Zealand, 46.0% N, granular product.
2. Superphosphate – Ravensdown Ltd, New Zealand, 9.0% P, granular product.
3. Lime – Big Value Lime, New Zealand, crushed Calcium Carbonate ($CaCO_3$), 37.0% Ca, powder product.
4. Al Sulphate – $Al_2 (SO_4)_3$, Egmont Pty Ltd, New Zealand, granular product.

3.2.6 Pots and Plant Measurement

All the pot trials grew corn (Zea mays) which was purchased as seed from Farm Source, an agricultural supplier in Hamilton. The pots were purchased from Bunnings Warehouse in Te Rapa, Hamilton. The pots were 15.5 cm high and a 17.0 cm diameter with a volume of 2.0 litres.

The plants from each pot trial were measured in centimetres using an industrial tape measure and weighed using a Kern EG Toploader balance from Sigma-Aldrich. The plants were dried using an electric temperature-controlled oven.

3.2.7 Pot Trial Soil Analysis

Soil analysis was conducted to determine the various chemical properties that are relevant to this study. Analysis for pH, total N, total P, Olsen P, and exchangeable Al was conducted using the following materials:

1. pH – Mantech, pH and Ion Analysis System with Automax 122 Sampler, Model MT-30.
2. Total N – Elemeter, Combustion Analyser, Model: Variomax Cube,
3. Total P – Thermo Scientific, ICP-OES, Model iCAP 6500. Nitric acid, Hydrochloric acid
4. Olsen P – Lachat, FIA, Model 8500 Series 1. Molybdate, Hydrochloric acid, Ascorbic acid
5. Exchangeable Al – Thermo Scientific, ICP-OES, Model iCAP 6500.

6. Calcium chloride

3.2.8 Column Leaching Experiment

The column leaching experiment used the same soil and the inputs as the pot trials. In addition to these materials, the column needed to be prepared for use and the experiment required materials that were unique to this study's experiment:

1. Plastic containers – 8.0cm x 8.0cm x 9.0cm, 2.0 litre capacity.
2. Mesh
3. Cable ties
4. PVC piping
5. Tubing
6. Plastic storage bottles
7. Peristaltic pump

3.2.9 Leachate Analysis

Analysis was conducted on the leachate from the column leaching experiments to determine the volume of leached N and P. The following materials were used for the leachate analysis:

1. Total P – Spectrophotometer, Biochrom, Model Libra S12.
   Ascorbic acid, Molybdate.
2. Total N – NO3 and NH4 ion meters.

3.3 METHODS

3.3.1 Compound-C Activation

The method to activate Compound-B in order to create Compound-C was as follows:

The concentrated monosilicic acid was diluted with distilled water at a ratio of 1:10. The solution was mixed with Compound-B at a proportion of 2.0 kg of Compound-B with 100.0 ml of the solution. The mixture was left to sit for one week before grinding the compounds and passing it through a 1.0 mm sieve (Bocharnikova et al., 2017).

3.3.2 Natural Mineral Analysis

The method to determine the concentration of active Si in each of the six natural Si-rich minerals was threefold:

1. Perform a water extraction and then an acid extraction of each mineral.
2. Perform an analysis of each extractant.
3. Use the combined results of each extractant and calculate the concentration of active Si.

Water Extraction – The water extraction, which is used to determine Actual Si, utilised the Mallen and Raily method to determine soluble monosilicic acid (Iler, 1979). The extraction procedure was as follows: 1) 6.0 grams of the mineral was placed into 100.0 mL containers. 2) 30.0 ml of distilled water was added to the container. After 1.0 day and again on the 4th day the material in the container was extracted by the following methodology (Bocharnikova et al., 2011). 3) After sitting for 24.0 hours the mixture was filtered and a clean extract was analysed for soluble monosilicic acid. 4) After 4.0 days another mixture was filtered and a clean extract was analysed for soluble monosilicic acid. 5) Monosilicic acid concentration was determined using the molybdate method (Iler, 1979).

Acid Extraction – The acid extraction, which is used to determine Potential Si, used the following procedure: 1) 2.0 grams of the mineral was placed into a 100.0 mL polyethylene container. 2) 20.0 mL of 0.1 Mole of hydrochloric acid (0.1M HCl) was added to the container and left for 24.0 hours. 3) A supernatant was centrifuged at 7,000.0 rpm for 15.0 minutes. 4) The concentration of Si was determined using the molybdate method (Iler, 1979).

Three replications for each water and acid extraction trial were conducted and the average and standard deviation for each sample was conducted using Microsoft Excel 2010.

It is important to determine both the actual (1 and 4.0-day water extraction) and the potential (acid extraction) Si concentration and are required to calculate the active Si concentration in the natural Si-rich minerals. The calculation method is the following: 10.0 x (1.0 day water extraction + 4.0 day water extraction) + acid extractable Si = active Si (Bocharnikova et al., 2011).

Based on the results from active Si analysis, three natural Si-rich minerals were selected for the pot trials and column leaching experiment. These minerals have been referred to throughout this study as Compound-A, Compound-B, and Compound-C.

3.3.3 Trial Soil Preparation

Brown soil of a loam texture was used for the pot trials and column leaching experiments. The soil was purchased after it had been put through an 8.0 mm sieve and it had a moisture content of 8.0 – 10.0%. After the soil was purchased it was then passed through a 3.0 mm sieve at the trial site. The soil was not subject to any drying, irrigation, or disinfection methodology before seed planting and was used as purchased following its final sieving. As little preparation as possible was performed on the soil in order to simulate actual farming conditions as closely as possible.

3.3.4 Trial Pots

The pots were placed on tables in three vertical rows of 64.0 horizontal rows. In order to simulate actual farming conditions as closely as possible the pots were not reshuffled at any time to obviate any microclimate effects. The tables were pressed up against a retaining wall for stability and to ensure the pots did not fall off. 2.0 kg of this soil was placed into each pot.

3.3.5 Pot Trial Inputs

The selected nutrient compounds were mixed into the top half of the soil with a multi-pronged metal instrument. Urea was applied at 1.2 grams per pot, which for a pot containing 2.0 kg of soil is the equivalent of 138.0 kilograms of N per hectare (kg/N/ha) or 300.0 kg/ha of Urea fertiliser, Superphosphate was applied 4.4 grams per pot, which is the equivalent of 100.0 kg/P/ha or 1.1 tonnes per hectare (t/ha) of

Superphosphate fertiliser. Lime was applied at two different rates, 4.0 grams per pot or 8.0 grams per pot, which is the equivalent of 2.0 t/ha and 4.0 t/ha respectively. The Si-rich compounds were applied at two different rates, 2.0 grams per pot or 4.0 grams per pot, which is the equivalent to 1.0 t/ha and 2.0 t/ha respectively (Imakumbili, 2019).

3.3.6 Seed Preparation

The seeds were germinated by soaking them in a 3.0% solution of hydrogen peroxide (H2O2) for 10.0 minutes before rinsing the seeds and placing them in a container on top of heavily moist filtering paper. The seeds were then covered in moist filtering paper and checked daily to ensure that the filtering paper was kept moist and to monitor the seeds' germination (Barba-Espín et al., 2012).

After the nutrients were applied to the pots a small plastic tube was used to make three holes in the soil of each pot, which were approximately 20.0mm in circumference and 20.0mm in depth. As soon as the seeds began to germinate, with a root length of 1.0 – 3.0mm, a single seed was placed into each of the three holes in every pot. The seeds were covered with soil and each pot was irrigated with 200.0ml of water.

3.3.7 Irrigation

A total of four pot trials were conducted outdoors in a natural environment in order to simulate farming conditions as closely as possible and the plants were subject to real-world conditions including rain, wind, and temperature. Natural conditions were used to avoid the benign controlled conditions of a laboratory or greenhouse where the stress features of Si may not be fully realised and lead to an imprecise understanding of the effects of Si (Epstein, 2009). In a controlled greenhouse or laboratory environment, the plants would typically require regular irrigation. However, because the plants were subject to the natural environment, irrigation was provided by the rain. The plants received additional irrigation only when the soil was beginning to dry out and on these occasions, the plants received 200.0 ml of tap water per pot (Ogunkunle & Beckett, 1988).

3.3.8 First Pot Trial

The trial consisted of ten tests and each test had three replications to determine result averages. The total number of pots used for the trial was thirty. The first pot trial was conducted to determine the effects of Si-rich compounds on corn yield. The protocols for the ten trials are shown in Table 11.

Table 11: *Protocols for the first group of pot trials*

Test	Soil	N	P	Lime	Si 1	Si 2	Si 3
1	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	0
2	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	0
3	2.0 kg	300.0 kg/ha	1.1 t/ha	2.0 t/ha	0	0	0
4	2.0 kg	300.0 kg/ha	1.1 t/ha	4.0 t/ha	0	0	0
5	2.0 kg	300.0 kg/ha	1.1 t/ha	0	1.0 t/ha	0	0
6	2.0 kg	300.0 kg/ha	1.1 t/ha	0	2.0 t/ha	0	0
7	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	1.0 t/ha	0
8	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	2.0 t/ha	0
9	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	1.0 t/ha
10	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	2.0 t/ha

The corn was grown for seven weeks before the following yield parameters were analysed using the analytical method described below:

1. Stalk length (centimetres)
2. Root length (centimetres)
3. Total Plant Length (centimetres)
4. Wet weight (grams)
5. Dry weight (grams)

Analytical Method: At the end of seven weeks, the plants were harvested from the pots and each of the plant's roots were washed with tap water separately (Böhm, 2012). The length of the stalk and the length of the roots from each plant were measured and weighed. Each whole plant was then dried at +65.0O C for 6.0 hours and then weighed again (Okalebo et al., 2002).

3.3.9 Second Pot Trial

The second trial consisted of thirty-four tests and each test had three replications to determine result averages. The total number of pots used for the trial was 102.0. The second pot trial was conducted to determine the effects of Si-rich compounds on the crop yield with N and P fertilisers applied at reduced rates. The application rate for both N and P were reduced by increments of 20.0%. The control application for Urea is 300.0 kg/ha, the second rate is reduced by 20.0% to 240.0 kg/ha, the third rate is reduced by 40.0% to 180.0 kg/ha, and the final rate is reduced by 60.0% to 120.0 kg/ha. The same incremental reduction also applied to P application rates. . The protocols for the thirty-four are shown in Table 12.

Table 12: *Protocols for the second group of pot trials.*

Test	Soil	N	P	Lime	Si-1	Si-2	Si-3
1	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	0
2	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	0
3	2.0 kg	300.0 kg/ha	1.1 t/ha	2.0 t/ha	0	0	0
4	2.0 kg	300.0 kg/ha	1.1 t/ha	4.0 t/ha	0	0	0
5	2.0 kg	300.0 kg/ha	1.1 t/ha	0	1.0 t/ha	0	0
6	2.0 kg	300.0 kg/ha	1.1 t/ha	0	2.0 t/ha	0	0
7	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	1.0 t/ha	0
9	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	1.0 t/ha
10	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	2.0 t/ha
11	2.0 kg	240.0 kg/ha	880.0 kg/ha	2.0 t/ha	0	0	0
12	2.0 kg	240.0 kg/ha	880.0 kg/ha	4.0 t/ha	0	0	0
13	2.0 kg	240.0 kg/ha	880.0 kg/ha	0	1.0 t/ha	0	0
14	2.0 kg	240.0 kg/ha	880.0 kg/ha	0	2.0 t/ha	0	0
15	2.0 kg	240.0 kg/ha	880.0 kg/ha	0	0	1.0 t/ha	0
16	2.0 kg	240.0 kg/ha	880.0 kg/ha	0	0	2.0 t/ha	0
17	2.0 kg	240.0 kg/ha	880.0 kg/ha	0	0	0	1.0 t/ha
18	2.0 kg	240.0 kg/ha	880.0 kg/ha	0	0	0	2.0 t/ha
19	2.0 kg	180.0 kg/ha	660.0 kg/ha	2.0 t/ha	0	0	0
20	2.0 kg	180.0 kg/ha	660.0 kg/ha	4.0 t/ha	0	0	0
21	2.0 kg	180.0 kg/ha	660.0 kg/ha	0	1.0 t/ha	0	0
`22	2.0 kg	180.0 kg/ha	660.0 kg/ha	0	2.0 t/ha	0	0
23	2.0 kg	180.0 kg/ha	660.0 kg/ha	0	0	1.0 t/ha	0
24	2.0 kg	180.0 kg/ha	660.0 kg/ha	0	0	2.0 t/ha	0

25	2.0 kg	180.0 kg/ha	660.0 kg/ha	0	0	0	1.0 t/ha
26	2.0 kg	180.0 kg/ha	660.0 kg/ha	0	0	0	2.0 t/ha
27	2.0 kg	120.0 kg/ha	440.0 kg/ha	2.0 t/ha	0	0	0
28	2.0 kg	120.0 kg/ha	440.0 kg/ha	4.0 t/ha	0	0	0
29	2.0 kg	120.0 kg/ha	440.0 kg/ha	0	1.0 t/ha	0	0
30	2.0 kg	120.0 kg/ha	440.0 kg/ha	0	2.0 t/ha	0	0
31	2.0 kg	120.0 kg/ha	440.0 kg/ha	0	0	1.0 t/ha	0
32	2.0 kg	120.0 kg/ha	440.0 kg/ha	0	0	2.0 t/ha	0
33	2.0 kg	120.0 kg/ha	440.0 kg/ha	0	0	0	1.0 t/ha
34	2.0 kg	120.0 kg/ha	440.0 kg/ha	0	0	0	2.0 t/ha

The corn was grown for seven weeks before the following yield parameters were analysed using the analytical method described below:

1. Stalk length (centimetres)
2. Root length (centimetres)
3. Total Plant Length (centimetres)
4. Wet weight (grams)
5. Dry weight (grams)

Analytical Method: At the end of seven weeks, the plants were harvested from the pots and each of the plant's roots were washed with tap water separately (Böhm, 2012). The length of the stalk and the length of the roots from each plant were measured and weighed. Each whole plant was then dried at +65.0O C for 6.0 hours and then weighed again (Okalebo et al., 2002).

3.3.10 Third Pot Trial

The third pot trial consisted of 10.0 tests and each test had three replications to determine result averages. The total number of pots used for the trial was 30.0. The third pot trial was conducted to determine the effects of Si-rich compounds on soil pH and Al toxicity. To induce low soil pH and a high level of Al in the soil, two applications, each application being 7.0 days apart, of Al sulphate at 100.0 micromoles (µmol), which is the equivalent of 0.68 grams per pot, was added to each pot (Ruiz et al., 2006). The first application was on day 21.0 of the trial and the second application was on day 35.0. Both applications of Al sulphate were made in conjunction with 200.0 ml of tap water per pot. The protocols for the ten trials are shown in Table 13.

Table 13: *Protocols for the third group of pot trials.*

Test	Soil	N	P	Lime	Si 1	Si 2	Si 3	Al
1	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	0	0
2	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	0	0
3	2.0 kg	300.0 kg/ha	1.1 t/ha	2.0 t/ha	0	0	0	200.0 µmol
4	2.0 kg	300.0 kg/ha	1.1 t/ha	4.0 t/ha	0	0	0	200.0 µmol
5	2.0 kg	300.0 kg/ha	1.1 t/ha	0	1.0 t/ha	0	0	200.0 µmol
6	2.0 kg	300.0 kg/ha	1.1 t/ha	0	2.0 t/ha	0	0	200.0 µmol
7	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	1.0 t/ha	0	200.0 µmol
8	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	2.0 t/ha	0	200.0 µmol
9	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	1.0 t/ha	200.0 µmol
10	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	2.0 t/ha	200.0 µmol

The corn was grown for seven weeks before the following yield and soil parameters were analysed using the analytical method described below:

1. Stalk length (centimetres)
2. Root length (centimetres)
3. Total Plant Length (centimetres)
4. Wet weight (grams)
5. Dry weight (grams)
6. pH level of the soil (pH units)
7. Exchangeable Al in the soil (mg/kg)

At the end of seven weeks, the plants were harvested from the pots and each of the plant's roots were washed with tap water separately (Böhm, 2012). The length of the stalk and the length of the roots from each plant were measured and weighed. Each whole plant was then dried at +65.0O C for 6.0 hours and then weighed again (Okalebo et al., 2002).

Soil samples were taken from each pot. Each soil sample was comprised of five randomly selected cores at 0 – 10.0 cm depth from each pot. The soil samples were analysed for soil pH and exchangeable Al.

Analytical Method: Soil samples were air-dried at 35.0 – 40.0oC and crushed to pass through a 2.0 mm screen. Soil pH was determined by 1:2 (v/V) soil: water slurry followed by potentiometric determination of pH. Exchangeable Al was determined by a 0.02M Calcium Chloride extraction followed by ICP-OES (Close & Powell, 1989).

3.3.11 Fourth Pot Trial

The trial consisted of ten tests and each test had three replications to determine result averages. The total number of pots used for the trial was thirty. The fourth pot trial was conducted to determine the effects of Si-rich compounds on N and P concentration in the soil and on P-fixation. The protocols for the ten trials are shown in Table 14.

Table 14: *Protocols for the fourth group of pot trials.*

Test	Soil	N	P	Lime	Si 1	Si 2	Si 3
1	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	0
2	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	0
3	2.0 kg	300.0 kg/ha	1.1 t/ha	2.0 t/ha	0	0	0
4	2.0 kg	300.0 kg/ha	1.1 t/ha	4.0 t/ha	0	0	0
5	2.0 kg	300.0 kg/ha	1.1 t/ha	0	1.0 t/ha	0	0
6	2.0 kg	300.0 kg/ha	1.1 t/ha	0	2.0 t/ha	0	0
7	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	1.0 t/ha	0
8	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	2.0 t/ha	0
9	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	1.0 t/ha
10	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	2.0 t/ha

The corn was grown for seven weeks before the following nutrient leaching and P-fixation parameters were analysed using the analytical method described below:

1. Total N in the soil (%)
2. Olsen P in the soil (mg/L)
3. Total P in the soil (mg/kg)

At the end of seven weeks, the plants were harvested from the pots and soil samples were taken from each pot. Each soil sample was comprised of five randomly selected cores at 0 – 10.0 cm depth from each pot (Okalebo et al., 2002). The soil samples were analysed for Total N, Olsen P, and total P.

Analytical Method: Soil samples were air-dried at 35.0 – 40.0oC and crushed to pass through a 2.0 mm screen. Total N was determined by NIR, calibration based on Total N by Dumas combustion. Total P was determined by Nitric/Nitric/hydrochloric digestion (based on US EPA 200.2) followed by ICPOES (Martin et al., 1994). Soluble P was determined by Olsen extraction followed by Molybdenum Blue colourimetry (Sims, 2000).

3.3.12 Column Experiment

The column experiment consisted of ten tests and each test had three replications. The total number of columns used for the trial was thirty. The column experiment was conducted to determine the ability of Si-rich compounds to hold nutrients in the soil and reduce N and P leaching. The experiment was also designed to determine the ability of Si-rich compounds to keep the nutrients it holds in the soil in a plant-available form. The protocols for the ten trials are shown in Table 15.

Table 15: *Protocols for the column leaching experiments.*

Test	Soil	N	P	Lime	Si 1	Si 2	Si 3
1	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	0
2	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	0
3	2.0 kg	300.0 kg/ha	1.1 t/ha	2.0 t/ha	0	0	0
4	2.0 kg	300.0 kg/ha	1.1 t/ha	4.0 t/ha	0	0	0
5	2.0 kg	300.0 kg/ha	1.1 t/ha	0	1.0 t/ha	0	0
6	2.0 kg	300.0 kg/ha	1.1 t/ha	0	2.0 t/ha	0	0
7	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	1.0 t/ha	0
8	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	2.0 t/ha	0
9	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	1.0 t/ha
10	2.0 kg	300.0 kg/ha	1.1 t/ha	0	0	0	2.0 t/ha

The column leaching experiments were conducted indoors at room temperature. The same soil, Si-rich compounds, lime, N, and P inputs that were used for the pot trials were also used for the column experiments. Columns were made from PVC piping that was 30.0 cm in height and 10.0 cm in diameter. The bottom of each column was covered with fly net mesh to stop soil loss. The mesh was kept in place with plastic cable ties (OECD, 2002). The same soil that was used for the pot trials was also used for the column leaching experiments and 2.0 kg of that soil was placed into each column. Nutrients were applied to the surface of each column and worked into the top 5.0 cm of the soil with a metal instrument.

Urea was applied at 1.2 grams per pot, which for a column containing 2.0 kg of soil is the equivalent of 138.0 kg/N/ha (300.0 kg/ha of Urea), Superphosphate was applied 4.4 grams per column, which is the equivalent of 100.0 kg/P/ha (1100.0 kg/ha of Superphosphate). Lime was applied at two different rates, 4.0 grams per column or 8.0 grams per column, which is the equivalent of 2,000.0kg/ha and 4,000.0 kg/ha respectively. The Si-rich compounds were applied at two different rates, 2.0 grams per column or 4.0 grams per column, which is the equivalent of 1,000.0 kg/ha and 2,000.0 kg/ha respectively (Imakumbili, 2019).

Each column was placed into a separate plastic container so that the leachate could be captured and collected. A peristaltic pump added distilled water to each column at a rate of 100.0 ml per hour for 24.0-hours. The percolated water was collected every two hours for the 24.0-hour period from each column and put in separate plastic bottles and then stored in a refrigerator before the leachate analysis was conducted.

The experiment ran for a period of 24.0-hours before the following leachate parameters were analysed using the analytical method described below:

1. Total N in the leachate (%)
2. Total P in the leachate (mg/L).
3. Total N, Total P, and Soluble P in the soil.

Analytical Method: The leachate from each column pot was collected and poured into a plastic container and refrigerated. The leachate samples were then filtered before nutrient analysis was conducted. Total N was determined with specific electrodes to measure nitrate (NO3) and ammonium (NH4) ions (Sparks et al., 2020). Total P in the percolate samples was analysed colourimetrically using a spectrophotometer at a wavelength of 880.0 nm (Carranzo, 2012).

3.3.13 Data Analysis

All the data that was obtained from the pot trial tests and column leaching experiment tests were subjected to a statistical analysis based on comparative methods using Fisher's Least Significant Different at the 5.0% level of significance (LSD test at $P < 0.05$). All calculations were completed using Microsoft Excel 2010 software.

CHAPTER 4

Results

"Nothing has such power to broaden the mind as the ability to investigate systematically and truly all that comes under thy observation in life."

- Marcus Aurelius

4.1 Introduction

The tests for this study followed a planned sequential pathway. This same pathway will be followed when describing the results of the tests:

1. Test One (SEM) determined which of the Si-rich compounds was most suitable for activation by synthetic concentrated monosilicic acid.
2. Test Two (Concentration of active Si) determined the concentration of active Si in each of the Si-rich compounds to determine which were the most suitable for use in the tests and experiments.
3. Test Three (pot trial one) determined crop yield produced by fertilising inputs.
4. Test Four (pot trial two) built on the results of Test Two by determining crop yield with reduced application rates of fertiliser inputs.
5. Test Five (pot trial three) builds on the results of Test Three and Four by determining the effects of fertilising inputs on soil pH, and the concentration of exchangeable Al.
6. Test Six (pot trial four) builds on the results of Test Three and Four by determining the effects of the fertilising inputs on nutrient concentration in the soil and soil P fixation.
7. Test Seven (column experiment) compliments Test Six with a leachate (water) analysis to determine the effects of the fertilising inputs on nutrient leaching and additional detail on nutrient concentrations in the soil.

4.2 Test One – SEM Analysis

The SEM images of the natural Si-rich minerals are provided in Figures 16 to 20. The images enabled the evaluation of the particle size and surface area of the minerals which were used as the determining factors for which Si-rich mineral would be activated with synthetic concentrated monosilicic acid. The largest particles belonged to the quartz sand at a range of 5.0 to 100.0 µm. The quartz sand also had a very smooth surface. Although the magnification of the SEM did show the pores typically found on zeolite particles (Terasaki et al., 2013) it was still strong enough to identify a particle size of 1.0 to 10.0 µm, which was the smallest of the quartz sand, SiO2 and zeolite minerals, and its rough surface.

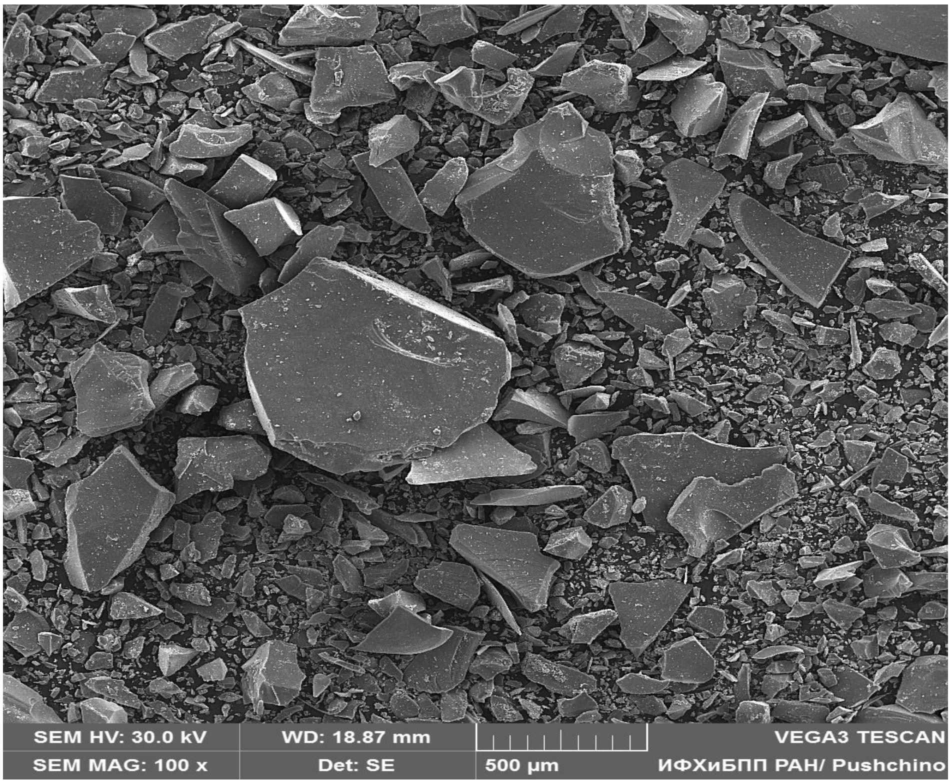


Figure 16: *Quartz Sand SEM Test.*

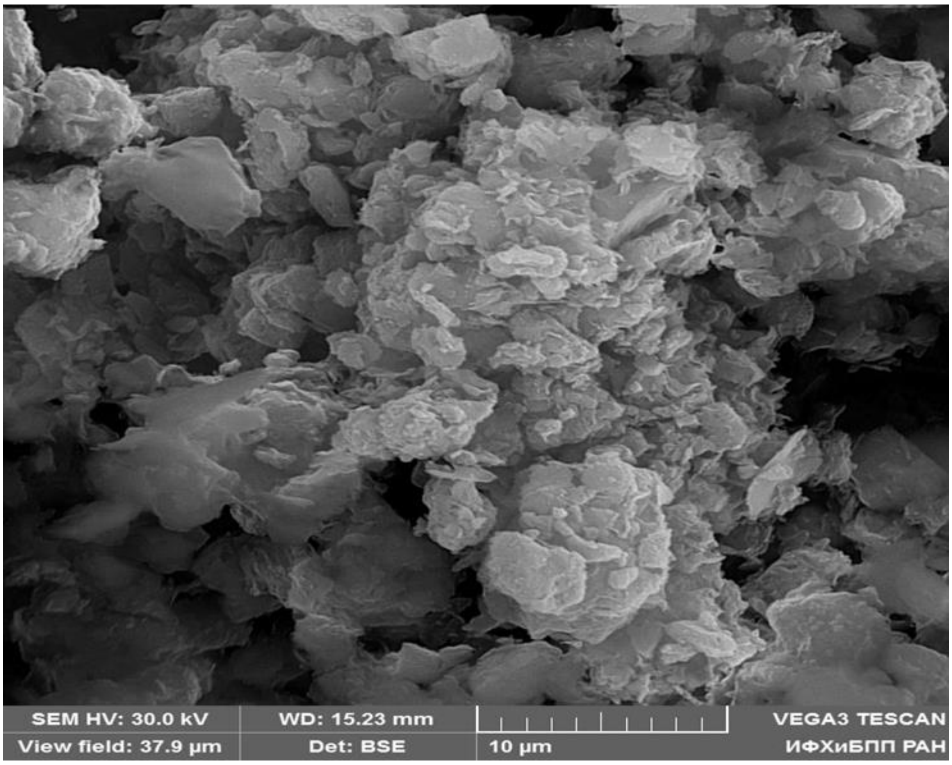


Figure 17: *Zeolite SEM Test.*

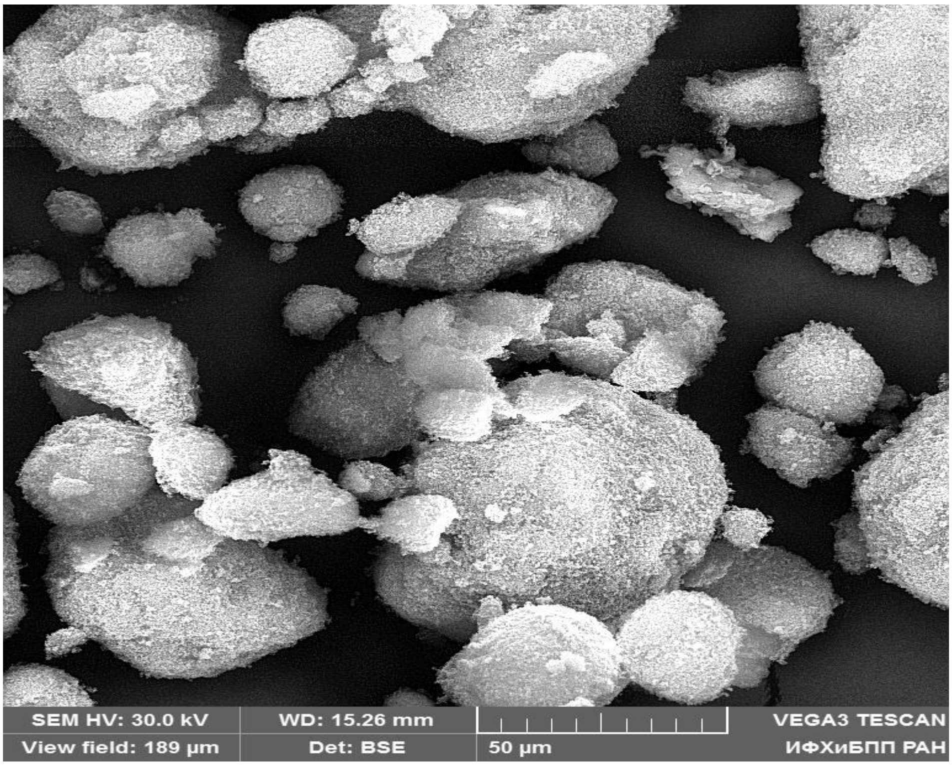


Figure 18: *SiO2 SEM Test.*

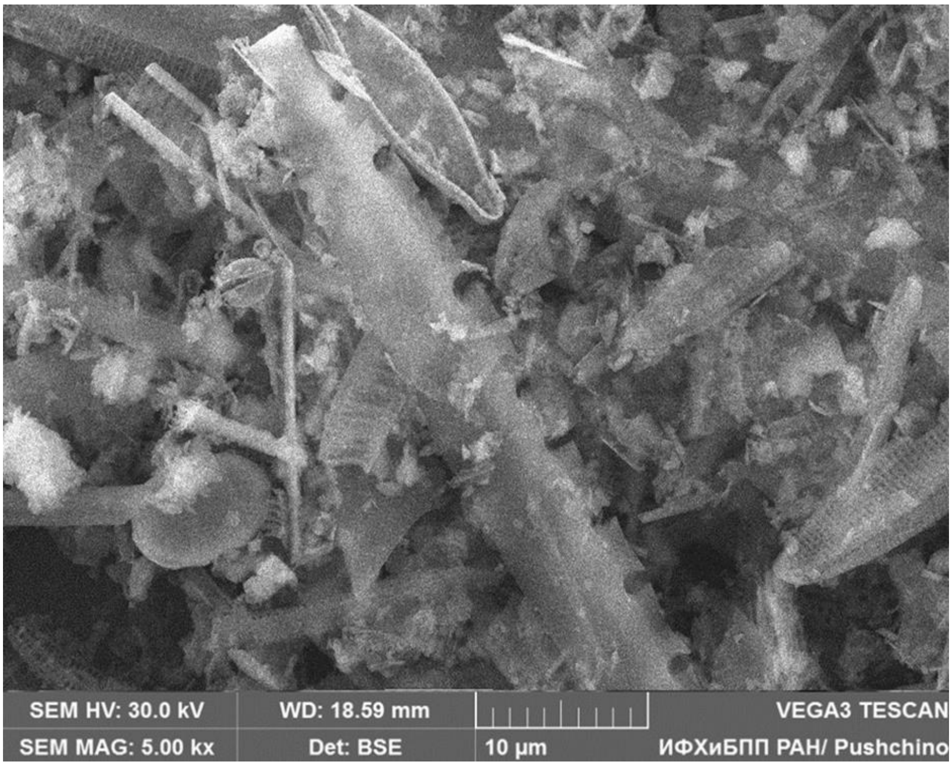


Figure 19: *Compound-A SEM Test.*

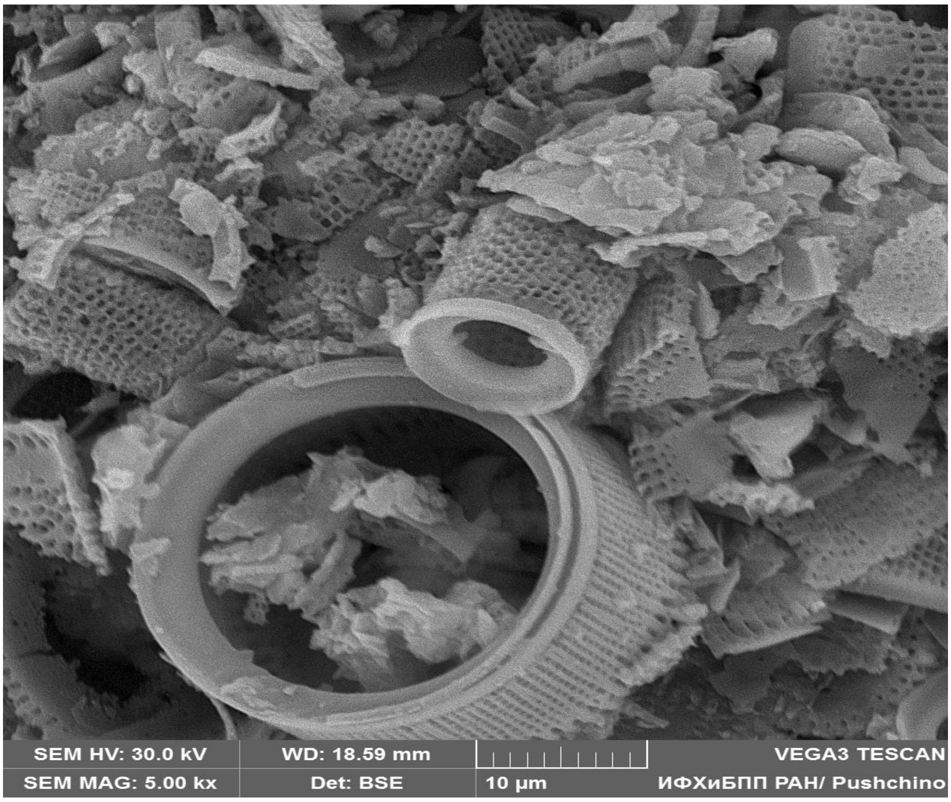


Figure 20: *Compound-B SEM Test.*

Compound-A and Compound-B had similar particle sizes to Zeolite at 2.0 to 5.0 µm and 1.0 to 5.0 µm respectively. The SEM clearly showed that Compounds A and B had a more complex structure than the other analysed minerals. Based on the particle sizes the approximate surface area of each mineral was determined for each: Quartz Sand<SiO2<Compound-A<Zeolite<Compound-B.

4.3 Test Two – Concentration of Active Silicon

Following the activation of Compound-B, which led to the creation of Compound-C, all the natural Si-rich minerals were analysed for their concentration of active Si. The results of the water and acid extraction analysis are presented in Table 16.

As a result of the activation of Compound-B with concentrated monosilicic acid, the highest concentration of active Si was found in Compound-C at 4,171.0 mg/kg. The activation process increased the active Si in Compound-B by 91.0 to 98.0%.

Despite having the second-largest particles and second smallest surface area, SiO2 had the second-highest concentration of active Si at 2,040 to 2,450.0 mg/kg or an average of 2,245.0 mg/kg. Zeolite, with the smallest particle size and largest surface area of all the minerals, had the next highest concentration of active Si at an average of 2,215.0 mg/kg. The remaining active Si tests corresponded to the results of the SEM tests. Compound-B had smaller particles and a larger surface area than Compound-A, which in turn had smaller particles and a larger surface area than quartz sand. Correspondingly, Compound-B had a higher concentration of active Si at an average of 2,140.0 mg/kg, than Compound-A, with its average of 1,875.0 mg/kg, which in turn was higher than quartz sand at an average of 63.0 mg/kg.

Table 16: *Active Si Concentration.*

Mineral	Water Extraction 1 Day	Water Extraction 4 Days	Acid Extraction	Active Silicon
	-------------------- Silicon mg/kg --------------------			
Quartz Sand	2 - 3	2 - 3	12 - 14	62 - 64
SiO2	60 - 85	74 - 90	700	2040 - 2450
Zeolite	50 - 52	72 - 78	955	2175 - 2255
Compound-A	42 - 45	64 - 70	160	1220 - 1310
Compound-B	45 - 48	75 - 80	900	2100 - 2180
Compound-C	101	153	1628	4171

4.4 Test Three (first pot trial) – Crop Yield.

The first pot trial was designed to determine what effects the Si-rich compounds had on crop yield in comparison to a combination of N and P fertilisers (N&P-only), and lime. The results showing the average length of each plant's stalk, root, and total length is presented in Figure 21 and the results showing the biomass, or average fresh and dry weight, of the plants is presented in Figure 22.

The application of N&P-only increased the stalk and root length of the plants, by 72.0% and 20.0% respectively, in comparison to the control protocols. The use of lime at 2.0 t/ha had a positive effect on the plant with the longest stalk length of the non-Si protocols at 45.0 cm and the longest roots of all non-Si protocols at 30.0cm. The application of 4.0 t/ha of lime had the opposite effect of 2.0 t/ha of lime on stalk length which was reduced by 11.0% in comparison to N&P-only and 15.0% in comparison to lime at 2.0 t/ha. The use of lime at 4.0 t/ha did increase root length if only 12.5% in comparison to N&P-only but reduced by 10.0% in comparison to lime at 2.0 t/ha.

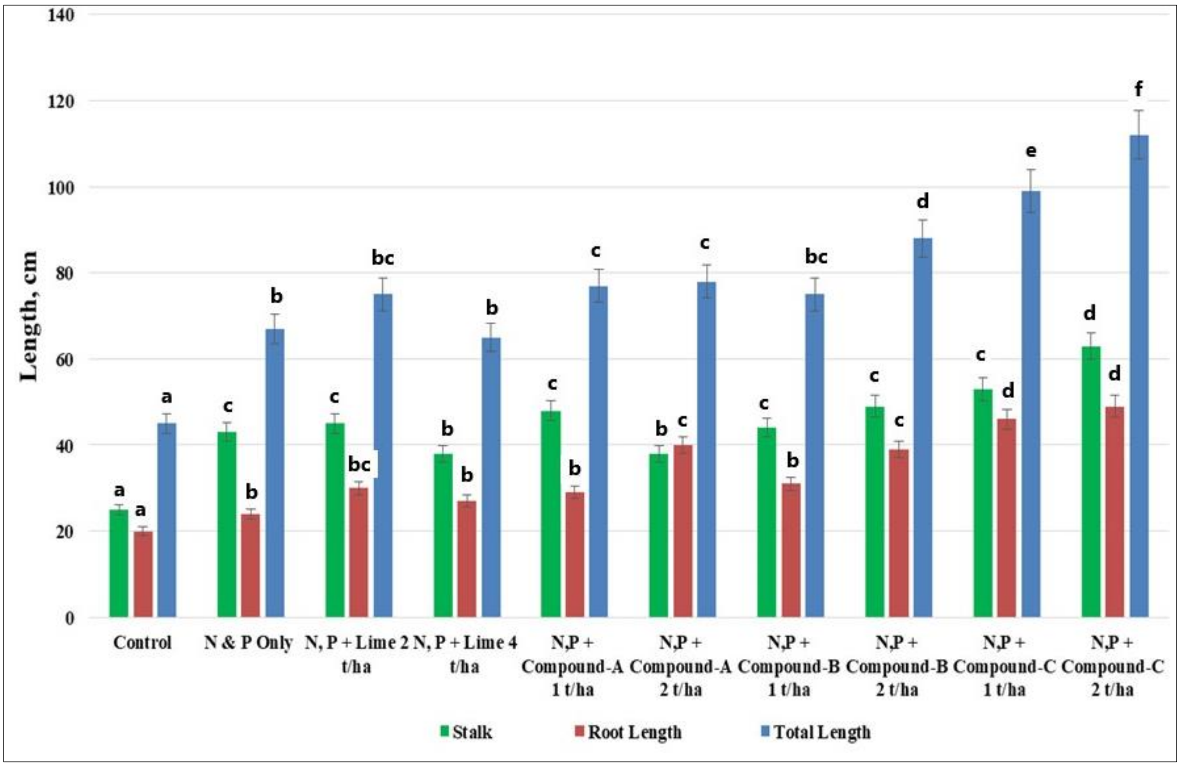


Figure 21: *Average stalk, root, and total plant length of the trial plants. Error bars represent standard deviation at 95% confidence. Letter codes denote significant differences between the control and treatments at 0.05% level.*

There are only two instances when the Si-rich compounds did not match or exceed the stalk length of N&P only or lime at 2.0 t/ha at 43.0cm and 45.0 cm respectively. Compound-A at 2.0 t/ha and Compound-B at 1.0 t/ha produced stalks at 38.0cm and 44.0cm respectively. There is only a single instance when the Si-rich compounds did not exceed the maximum root length of all the non-Si protocols at 30.0 cm produced by lime at 2.0 t/ha. In that single instance, Compound-A at 1.0 t/ha produced an average root length of 29.0 cm.

The maximum stalk and root length were produced by Compound-C at 2.0 t/ha with 63.0 cm and 49.0 cm respectively. This represented an increase of 40.0% in stalk length in comparison to lime at 2.0 t/ha and 18.0% in comparison to the next highest performing Si-rich compound at 46cm produced by Compound-C at 1.0 t/ha. The root length of Compound-C at 2.0 t/ha represents a 63.0% increase in comparison to lime at

2.0 t/ha and a 6.0% increase in comparison to Compound-C at 1.0 t/ha. Compound-C at the lower rate of 1.0 t/ha produced longer stalks and roots than both rates of Compounds A and B.

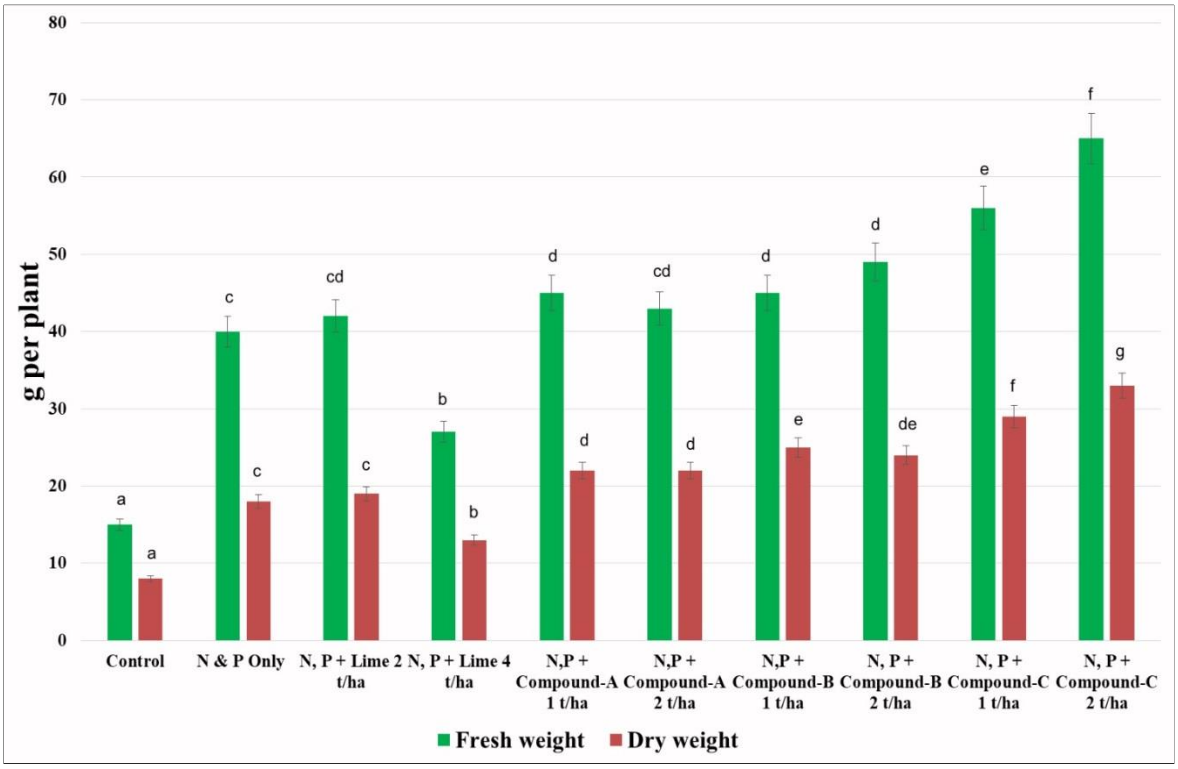


Figure 22: *Average biomass, by fresh and dry weight, of the trial plants. Error bars represent standard deviation at 95% confidence. Letter codes denote significant differences between the control and treatments at 0.05% level.*

The application of N&P only significantly increased the biomass of the plants in comparison to the control by 166.0% for the fresh weight and 125.0% for the dry weight. The addition of 2.0 t/ha of lime improved the biomass of N&P only slightly but the addition of 4.0 t/ha decreased biomass by 32.0% for fresh weight and 27.0% for dry weight in comparison to N&P only, and 35.0% for fresh weight and 31.0% for dry weight in comparison to lime at 2.0 t/ha.

The heaviest fresh weight biomass for the non-Si protocols was produced by the 2.0 t/ha of lime at 42.0 grams for fresh weight and 19.0 grams for dry weight. The Si-rich protocols all produced heavier fresh and dry weight biomass than non-Si plants. Compound-A at 2.0 t/ha produced the lightest biomass at 43.0 grams for fresh weight and 22.0 grams for dry weight which was 2.0% heavier than lime at 2.0 t/ha for fresh weight and 15.0% heavier for dry weight. Compound-C at 2.0 t/ha produced the heaviest fresh weight of the protocols at 65.0 grams and the heaviest dry weight at 33.0 grams. For fresh and dry weight, Compound-C at 2.0 t/ha produced 170.0% and 73.0% more than lime at 2.0 t/ha and 16.0% and 13.0% more than Compound-C at 1.0 t/ha which was the next highest producing Si-rich compound.

A picture showing a comparison of the above-ground biomass of the plants from the first pot trial is shown in Figure 23.

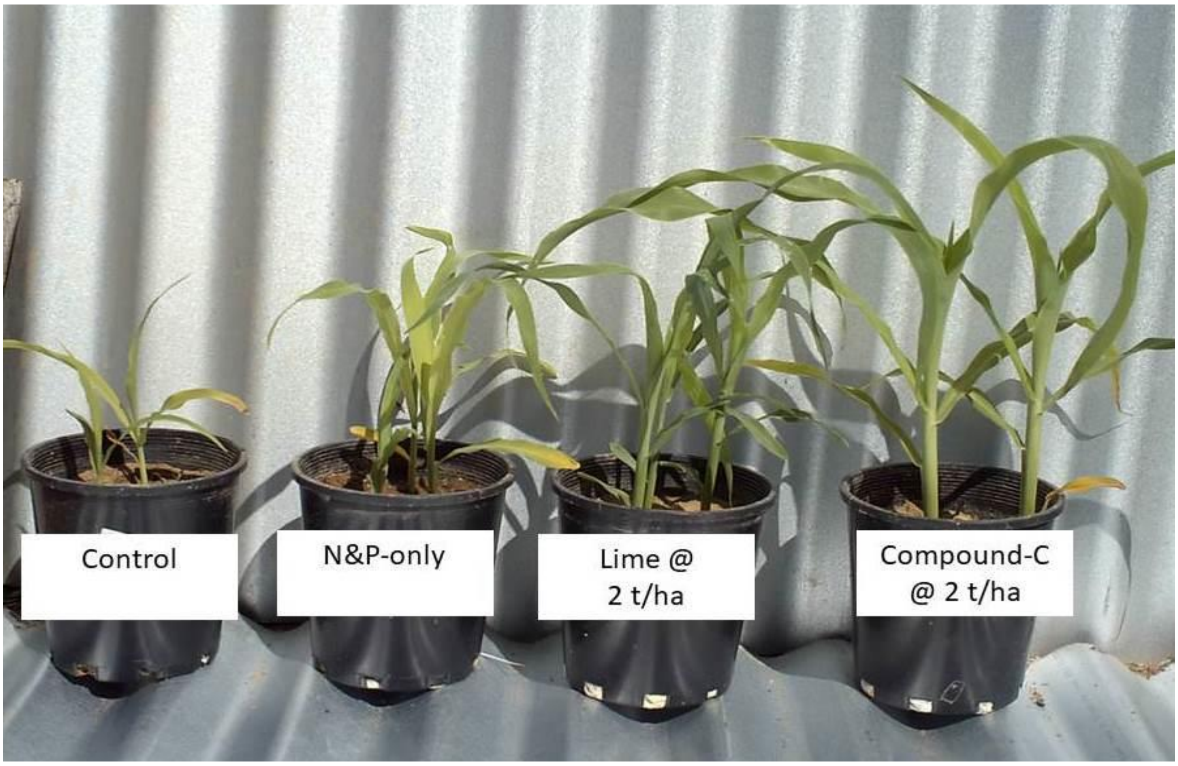


Figure 23: *Plant comparison at 4-weeks, first pot trial.*

Data detailing the average length and weight of the plants produced by each Si-rich and non-Si fertiliser protocol in direct comparison to the full application rate of N&P-only is presented in Table 17.

Table 17: *The % increase of the length and weight of all plants in comparison to the plants produced by N&P-only*

	Stalk Length	Root Length	Total Length	Fresh Weight	Dry Weight
	------------------- cm		--------------------	------- g per plant	------
N & P Only	100.0	100.0	100.0	100.0	100.0
N, P + Lime 2.0 t/ha	104.7	125.0	111.9	105.0	105.6

N, P + Lime 4.0 t/ha	88.4	112.5	97.0	67.5	72.2
N, P + Compound-A 1.0 t/ha	111.6	120.8	114.9	112.5	122.2
N, P + Compound-A 2.0 t/ha	88.4	166.7	116.4	107.5	122.2
N, P + Compound-B 1.0 t/ha	102.3	129.2	111.9	112.5	138.9
N, P + Compound-B 2.0 t/ha	114.0	162.5	131.3	122.5	133.3
N, P + Compound-C 1.0 t/ha	123.3	191.7	147.8	140.0	161.1
N, P + Compound-C 2.0 t/ha	146.5	204.2	167.2	162.5	183.3

4.5 Test 4 (second pot trial) – Crop Yield with Reduced Fertiliser Rates.

The second trial was designed to determine what effects the Si-rich compounds had on crop yield with a 20.0, 40.0, and 60.0% reduction in the application rates of N and P fertilisers. The results showing the average length of each plant's stalk, root and total length with a 20.0% reduction in N and P fertiliser application is presented in Figure 24.

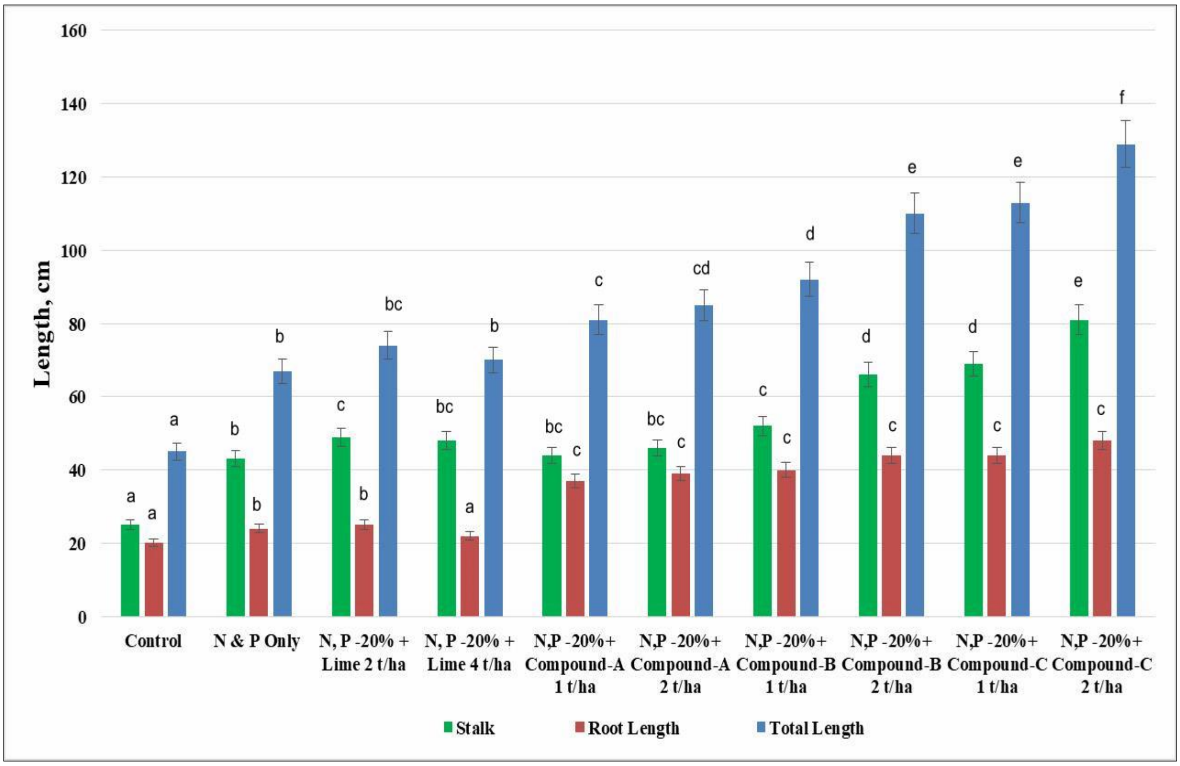


Figure 24: *Average stalk, root and total length of the trial plants grown with a 20% reduction in N and P application. Error bars represent standard deviation at 95% confidence. Letter codes denote significant differences between the control and treatments at 0.05% level.*

The results from the 20.0% fertiliser reduction trial followed a similar pattern to the first pot trial. The application of lime at 2.0 t/ha together with the reduced rate of

N&P increased the length of the stalk by 14.0% and the roots by 4.0% in comparison to the full rate of N&P fertilisers. The higher application rate of 4.0 t/ha of lime did not perform as well as the lower rate but it still increased stalk length by 11.0% but root length was reduced by 8.0%. The longest root and stalk length of 49.0 cm and 25.0 cm respectively, among the non-Si protocols was the lime at 2.0 t/ha. The lime at 2.0 t/ha outperformed both application rates of Compound-A for the stalk length but did not perform as well as any Si-rich compounds for root length. The increased root length of Si-rich compound protocols also meant that they all outperformed the lower rate of lime for the total length of the plant. With the total plant length of 74.0cm for lime at 2.0 t/ha the lowest-performing Si-rich- compound, Compound-A at both rates, outperformed the lime at 2.0 t/ha by 9.0% and 14.0% respectively. Compound-B at the lower and high rate and Compound-3 at the lower and higher rate increased total plant length by 24.0, 48.0, 52.0, and 74.0% respectively.

In general, the 20.0% reduction of N and phosphorous fertiliser performed better than the standard rate of N and phosphorous fertiliser. Except for a single instance, Compound-A at 1.0 t/ha, the reduced rate of P produced longer stalks than the full rate of phosphorus. This was true even for the pots that did not have any Si-rich compound. The full rate of N&P + lime at 2.0 t/ha and 4.0 t/ha produced stalk lengths of 45.0 and 38.0cm respectively in comparison to lime at 2.0 t/ha and 4.0 t/ha with 20.0% less N and P producing stalk lengths of 49.0 and 48.0cm respectively, which represented an increase of 8.0% for the 2.0 t/ha protocol and 26.0% for the 4.0 t/ha protocol. The longest stalk produced by a 20.0% reduction protocol was 81.0 cm for Compound-C at 2.0 t/ha. This was a 28.0% increase over the longest stalk produced by a full rate protocol of 63.0cm for Compound-C at 2.0 t/ha. Both Compound-C at 1.0 t/ha and Compound-B at 2.0 t/ha at a 20.0% reduced rate of N&P produced stalks that were longer than the full rate for Compound-C at 2.0 t/ha. The comparison for root length was not as clear cut in favour of the reduced rate of N&P as was the stalk length. In 5 out of 8 instances the standard rate produced longer roots than the 20.0% reduction. However, due to the superior stalk length, in every case except one, the reduced rates produced a longer total plant than the standard rate of N&P. The only exception was for the 2.0 t/ha of lime protocols which produced a total plant length of

75.0cm and the reduced rate produced a 74.0cm total plant length. The longest total plant length was Compound-C at 2.0 t/ha with the reduced rate of N&P at 129.0cm which was 15.0% longer than the longest total plant length produced with a full rate of fertiliser at 112.0cm for Compound-C at 2.0 t/ha.

Except for lime at 2.0 t/ha, all the tests with a 20.0% reduction in N&P produced a longer total plant than the corresponding tests with a full rate of N&P. The 20.0% reduction in N&P tests produced a longer total plant than the full rate of N&P tests by an average of 12.0%.

The results showing the comparison of the average fresh and dry weight of the plants with a 20.0% reduction in N&P is presented in Figure 25.

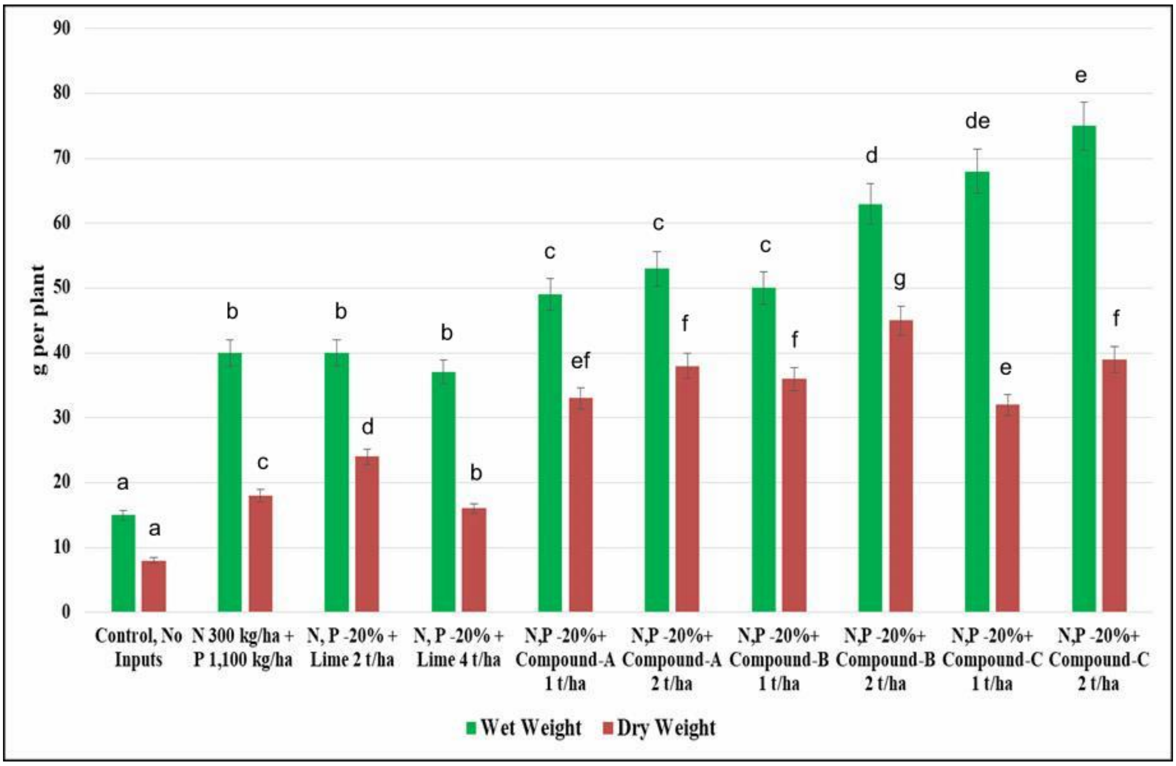


Figure 25: *Average biomass, by fresh and dry weight, of the trial plants grown with a 20% reduction in N and P application. Error bars represent standard deviation at 95% confidence. Letter codes denote significant differences between the control and treatments at 0.05% level.*

The application of N&P-only + lime at 2.0 t/ha increased the biomass of the plants in comparison to the control by 166.0% for the fresh weight and 200.0% for the dry weight. While the fresh weight was the same between N&P-only and N&P-only + lime at 2.0 t/ha the reduced rate of N&P-only produced a 33.0% increase in dry weight. The use of 4.0 t/ha of lime produced a smaller plant biomass than lime at 2.0 t/ha.

All three Si-rich compounds at both the high and low rate of application produced a greater crop yield than all non-Si rich protocols. Compound-C produced an average fresh weight of 75.0 grams and an average dry weight of 39.0 grams. However, while producing a fresh weight that was 19.0% smaller, Compound-B at 2.0 t/ha produced a heavier dry weight than Compound-C at 2.0 t/ha by 15.0%. The highest fresh weight produced by a Si-rich compound was 75.0 grams and the highest dry weight was 45.0 grams which were heavier than the heaviest non-Si compound of 37.0 and 16.0 grams respectively by 102.0% for fresh weight and 181.0% for dry weight. The lightest fresh weight and dry weight produced by Si-rich compounds were 49.0 grams and 32.0 grams respectively which were heavier than the heaviest non-Si rich compound by 32.0% and 100.0% respectively.

Data detailing the average length and weight of the plants produced by each Si-rich and non-Si fertiliser protocol in direct comparison to the full application rate of N&P-only is presented in Table 18.

Table 18: *The % increase of the length and weight of the trial plants, grown with a 20% reduction in N and P application, in comparison to N&P only.*

	Stalk Length	**Root Length**	**Total Length**	**Fresh Weight**	**Dry Weight**
	------------ cm --------		---------- g per plant ----------		
N&P Only	100.0	100.0	100.0	100.0	100.0
N, P -20% + Lime 2.0 t/ha	114.0	104.2	110.4	100.0	133.3
N, P -20% + Lime 4.0 t/ha	111.6	91.7	104.5	92.5	88.9
N,P -20%+ Compound-A 1.0 t/ha	102.3	154.2	120.9	122.5	183.3
N,P -20%+ Compound-A 2.0 t/ha	107.0	162.5	126.9	132.5	211.1
N,P -20%+ Compound-B 1.0 t/ha	120.9	166.7	137.3	125.0	200.0
N,P -20%+ Compound-B 2.0 t/ha	153.5	183.3	164.2	157.5	250.0
N,P -20%+ Compound-C 1.0 t/ha	160.5	183.3	168.7	170.0	177.8
N,P -20%+ Compound-C 2 t/ha	188.4	200.0	192.5	187.5	216.7

Except for lime at 2.0 t/ha, all tests with a 20.0% reduction in N&P produced a heaver fresh weight than the corresponding tests with a full rate of N&P. All the 20.0% reduction in N&P tests produced a heavier dry weight than the corresponding tests with the full rate of N&P. The average increase in fresh and dry weight of the 20.0% reduction in N&P tests was 16 and 40.0% respectively.

The results showing the average length of each plant's stalk, root, and total length with a 40.0% reduction in N and P fertiliser application is presented in Figure 26.

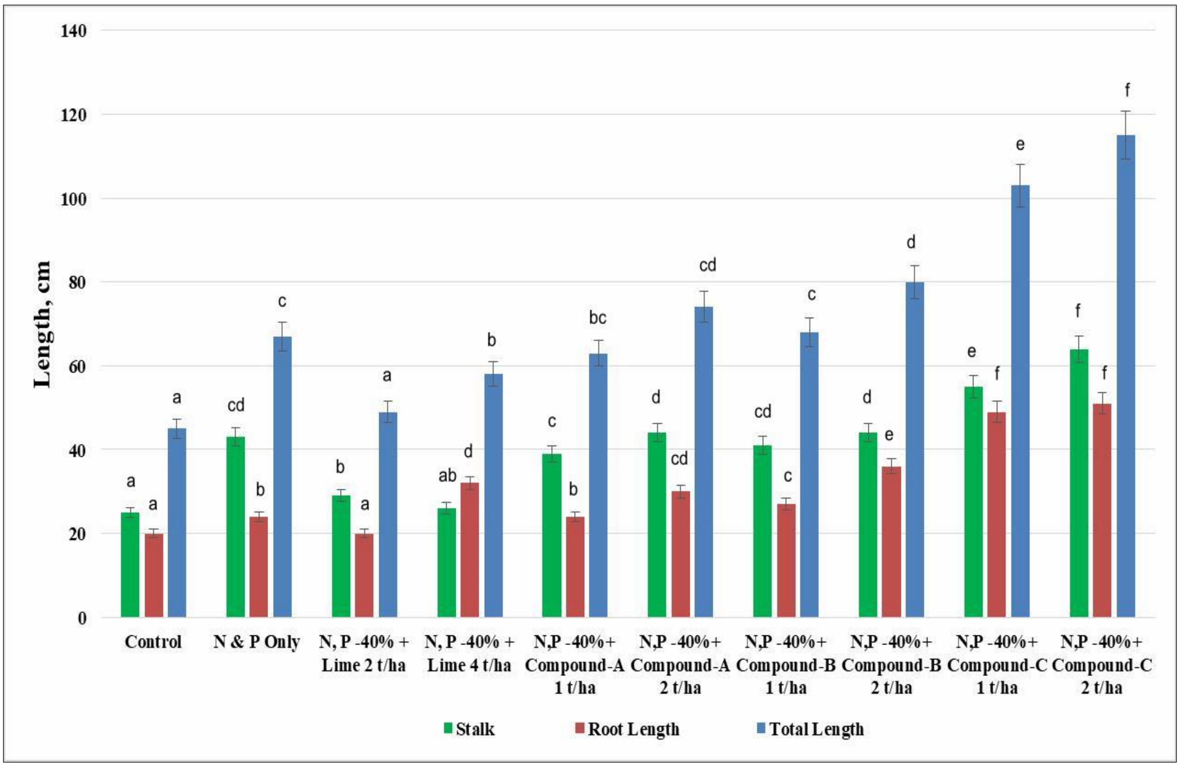


Figure 26: *Average stalk, root, and total length of the trial plants grown with a 40% reduction in N and P application. Error bars represent standard deviation at 95% confidence. Letter codes denote significant differences between the control and treatments at 0.05% level.*

The application of lime at 2.0 t/ha together with the 40.0% reduced rate of N and P produced a similar plant biomass to lime at 4.0 t/ha with stalk length being 42.0 cm and 45.0 cm, and root length being 27.0 cm and 22.0 cm respectively. The difference in total plant length between the lower and higher application rate of lime was less than 2.9%. In contrast to all the previous tests, lime at the higher application rate of 4.0 t/ha produced a longer stalk length than the longest produced by Si-rich compounds by 40.0%. However, lime at 4.0 t/ha produced the shortest root length of all the tests at 22.0 cm which was 22.0% shorter than lime at 2.0 t/ha, 59.0% shorter than the shortest root length produced by a Si-rich compound, and 100.0% shorter than the longest root length produced by a Si-rich compound. Although producing a shorter root length than lime at 4.0 t/ha, the lime at 2.0 t/ha produced a longer stalk length than all the Si-rich compounds. The longest stalk was produced by Compound-B at 2.0 t/ha which was 31.0% shorter than lime at 2.0 t/ha. Like the lime applied at 4.0 t/ha, the root length produced by lime at 2.0 t/ha was shorter than all the roots produced by Si-rich compounds.

Although the non-Si compounds produced a longer stalk by an average of 46.7%, the Si-rich compounds produced longer roots by an average of 63.7%. Compound-C at 2.0 t/ha and 1.0 t/ha, and Compound-B at 2.0 t/ha produced a total plant length of 74.0, 70.0, and 72.0 cm respectively. The longest total plant length produced by the non-Si compounds were lime at 2.0 t/ha, and both lime at 4.0 t/ha and N&P-only at 69.0 and 67.0 cm respectively. The shortest total plant length produced by the Si-rich compounds were equal or very similar to the non-Si rich compound at 64.0 cm for Compound-B at 1.0 t/ha, 67.0 cm for Compound-A at 1.0 t/ha, and 69.0 cm for Compound-A at 2.0 t/ha.

All the tests with a 40.0% reduction in N&P produced a shorter total length of plant than the corresponding tests with a 20.0% reduction in N&P. With the single exception of lime at 4.0 t/ha, all the tests with a 40.0% reduction in N&P produced a shorter total length of plant than the corresponding tests with a full rate of N&P. The 20.0% reduction and the full rate of N&P produced a longer total plant than the 40.0% reduction in N&P tests by 36.0 and 21.0% respectively.

The results showing the comparison of the average fresh and dry weight of the plants with a 40.0% reduction in N&P is presented in Figure 27.

A 40.0% reduction in N&P had a significant negative effect on crop yield for the non-Si protocols. Lime applied at 2.0 and 4.0 t/ha produced a lighter fresh weight than N&P at the full rate of application by 8.0 and 29.0% respectively.

Lime at 2.0 t/ha produced heavier dry weight than the full rate of N&P by 18.0% and lime at 4.0 t/ha was outperformed by N&P by 12.0%. All the Si-rich compounds produced a heavier fresh weight than the non-Si protocols and except for Compound-A at 1.0 t/ha, all the Si-rich compounds produced a heavier dry weight. The heaviest fresh and dry weight was produced by Compound-C at 2.0 t/ha which was 35.0 and 42.0% heavier than the heaviest non-Si compound respectively. The lightest fresh weight produced by a Si-rich compound was Compound-A at 1.0 t/ha at 43.0 grams was 7.5% heavier than the heaviest non-Si compound. The lightest dry weight produced by a Si-rich compound was 20.0 grams for Compound-A at 1.0 t/ha was 5.0% lighter than the heaviest dry weight produced by a non-Si protocol.

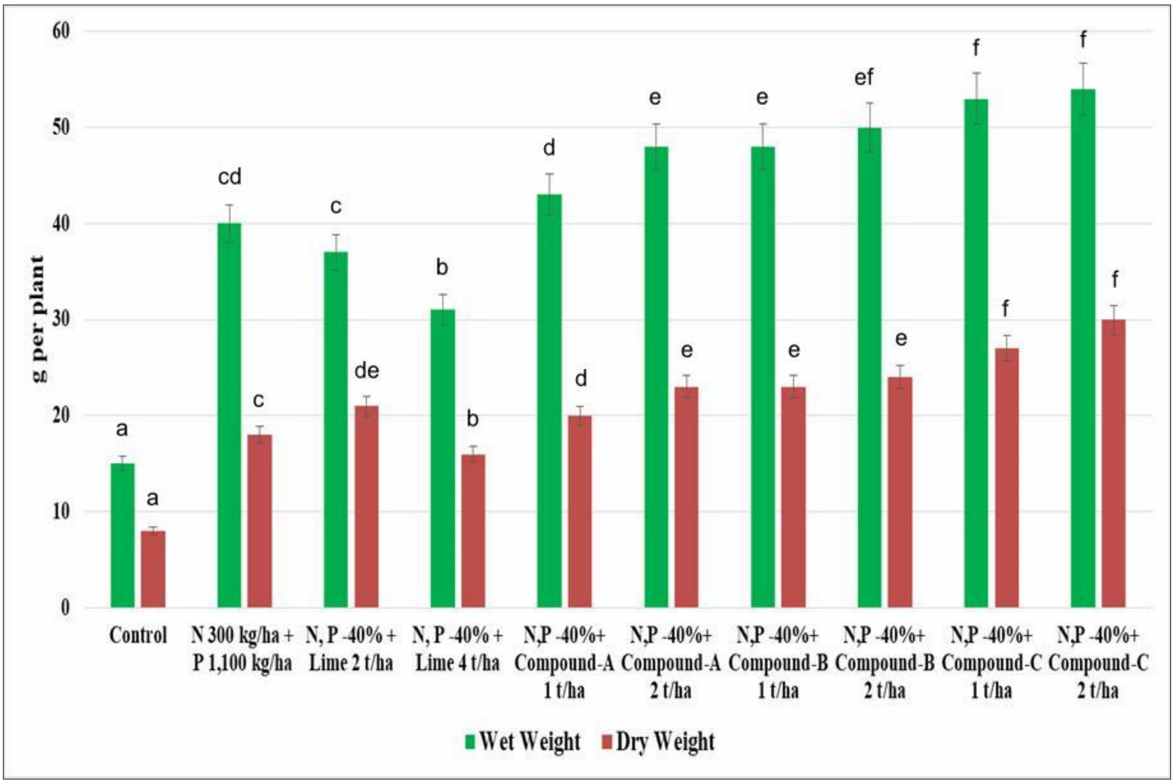


Figure 27: *Average biomass, by fresh and dry weight, of the trial plants grown with a 40% reduction in N and P application. Error bars represent standard deviation at 95% confidence. Letter codes denote significant differences between the control and treatments at 0.05% level.*

All the tests with a 40.0% reduction in N&P produced a smaller crop yield than the 20.0% reduction tests. The non-Si protocols produced lighter fresh weight than the corresponding tests with a 20.0% reduction in N&P. With the single exception of lime at 4.0 t/ha all the tests with a 40.0% reduction in N&P. Except for lime at 4.0 t/ha which was equal to 16.0 grams each, the dry weight for the non-Si tests were also lighter for the 40.0% reduction protocols. The 40.0% reduction in N&P for the Si-rich compounds were lighter for both fresh and dry weight than the corresponding tests with a 20.0% reduction in N&P by an average of 20.0 and 51.0% respectively. The Si-rich compounds with a 40.0% reduction in N&P were generally similar to the corresponding tests with a full rate of N&P for fresh and dry weight. On average there was a 2.0% difference between the 40.0% reduction and the full rate at producing fresh weight and a 5.0% difference at producing dry weight. The average difference between the 40.0% and 20.0% reduced N&P rates was significant with the average difference between the two, being 20.0% and 51.0% for fresh and dry weight respectively, in favour of the 20.0% reduced rate.

Data detailing the average length and weight of the plants produced by each Si-rich and non-Si fertiliser protocol in direct comparison to the full application rate of N&P-only is presented in Table 19.

Table 19: *The % increase of the length and weight of the trial plants, grown with a 40% reduction in N and P application, in comparison to N&P only.*

	Stalk Length	**Root Length**	**Total Length**	**Fresh Weight**	**Dry Weight**
	----------- cm --------		---------- g per plant ----------		
N&P Only	100.0	100.0	100.0	100.0	100.0
N, P -40% + Lime 2.0 t/ha	97.7	112.5	103.0	92.5	116.7
N, P -40% + Lime 4.0 t/ha	104.7	91.7	100.0	77.5	88.9
N,P -40%+ Compound-A 1.0 t/ha	69.8	154.2	100.0	107.5	111.1
N,P -40%+ Compound-A 2.0 t/ha	67.4	166.7	103.0	120.0	127.8
N,P -40%+ Compound-B 1.0 t/ha	67.4	145.8	95.5	120.0	127.8
N,P -40%+ Compound-B 2 t/ha	74.4	166.7	107.5	125.0	133.3
N,P -40%+ Compound-C 1 t/ha	62.8	179.2	104.5	132.5	150.0
N,P -40%+ Compound-C 2 t/ha	69.8	183.3	110.4	135.0	166.7

The results showing the average length of each plant's stalk, root, and total length with a 60.0% reduction in N and P fertiliser application is presented in Figure 28.

The non-Si protocols of the 60.0% reduced N&P application produced a lower yield, in general than the 40.0% reduced application rate of N&P. Lime at 2.0 t/ha and 4.0 t/ha produced 43.0 and 36.0 cm stalk length respectively for the 60.0% reduced

N&P rate and 42.0 and 45.0 cm for the 40.0% reduced N&P rate. The root length was 20.0 and 19.0 cm respectively for the 60.0% reduced N&P protocols and 27.0 and 22.0 cm respectively for the 40.0% reduced N&P protocols. On average, the lime protocols of the 40.0% reduced N&P rate produced the longer stalks by 114.0% at 2.0 t/ha and 89.0% for 4.0 t p/ha and longer roots by 55.0% at 2.0 t p/ha and 104.0% at 4.0 t p/ha. The average total length of the plant for lime at 2.0 t/ha and 4 t p/ha for the 60.0% reduced rate of N&P 63.0 and 55.0 cm respectively. The corresponding tests at a 40.0% reduced rate of N&P were 69.0 and 67.0 cm respectively which equates to a longer total length of the plant by 9.0 and 21.0% respectively.

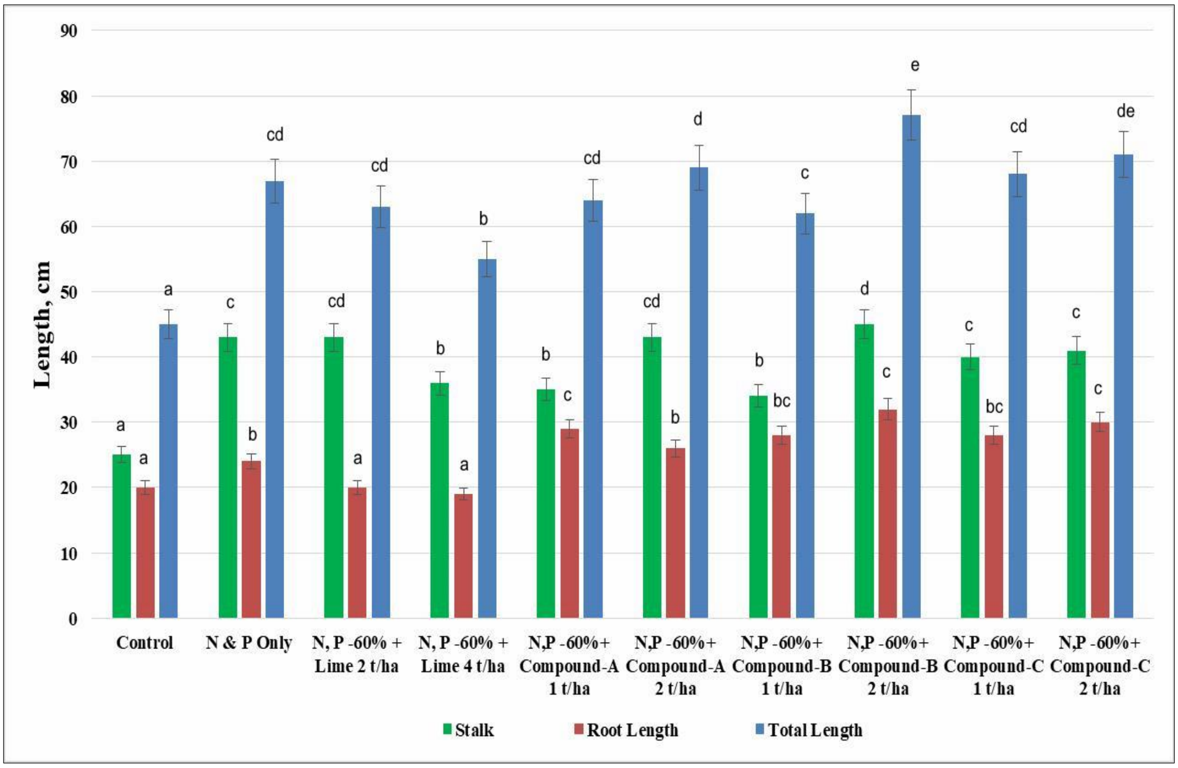


Figure 28: *The average stalk and root length of the trial plants grown with a 60% reduction in N and P application. Error bars represent standard deviation at 95% confidence. Letter codes denote significant differences between the control and treatments at 0.05% level.*

The results showing the comparison of the average fresh and dry weight of the plants with a 60.0% reduction in N&P is presented in Figure 29.

The Si-rich compounds at a 60.0% reduction in N&P produced longer stalks, by an average of 34.0% than the corresponding tests at a 40.0% reduction in N&P. However, the Si-rich compounds at a 40.0% reduction produced longer roots, by an average of 38.0%, than the corresponding tests at a 60.0% reduction of N&P. The

40.0% reduced rate of N&P produced a longer total plant by an average of 27.0% than the 60.0% reduced rate of N&P.

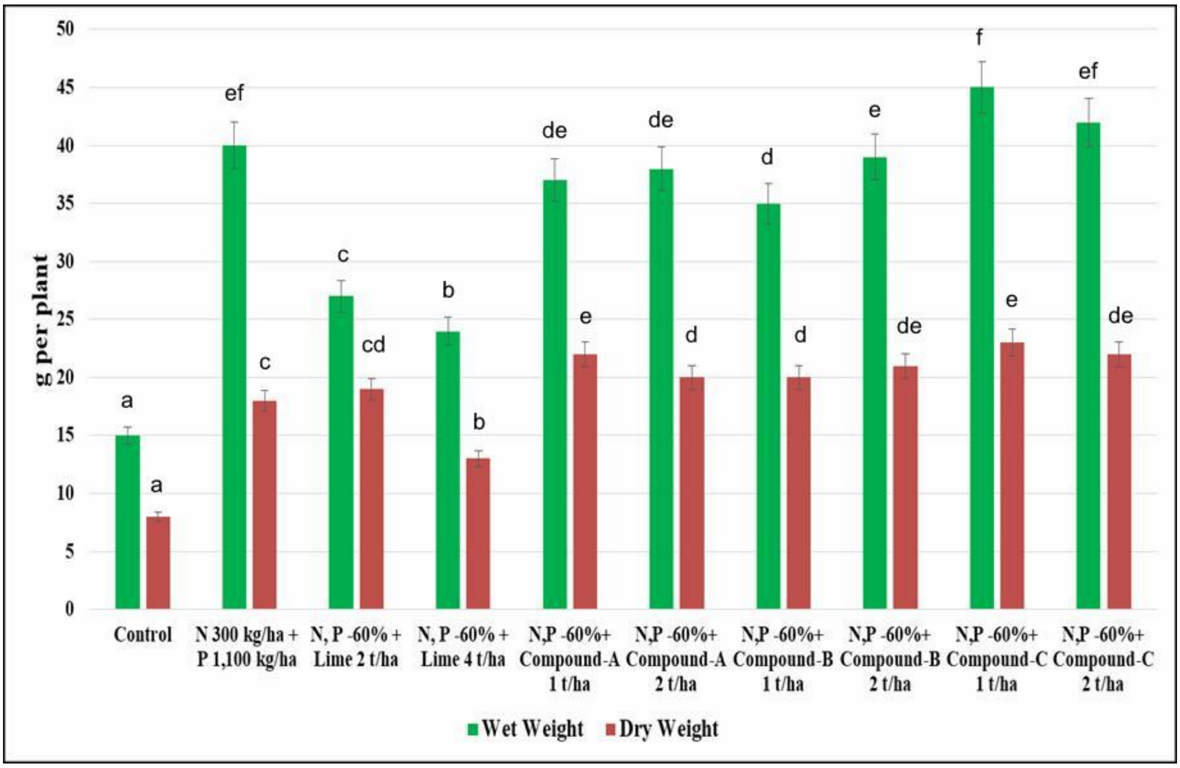


Figure 29: *The average biomass, by fresh and dry weight, of the trial plants grown with a 60% reduction in N and P application. Error bars represent standard deviation at 95% confidence. Letter codes denote significant differences between the control and treatments at 0.05% level.*

The longer average total plant produced by a non-Si pot at the 40.0% reduced rate translated over to the fresh and dry weights of the plants. The heaviest non-Si fresh weight plant produced by the 40.0% reduced rate of N&P was 37.0% heavier than the heaviest non-Si plant at a 60.0% reduced rate of N&P.

The lightest non-Si fresh weight plant produced by the 40.0% reduced rate of N&P was 14.0% heavier than the heaviest non-Si plant at a 60.0% reduced rate of N&P. Lime at 2.0 and 4 t p/ha at the 40.0% reduced rate of N&P also produced heavier average dry weights than the corresponding tests at 60.0% reduced rate of N&P.

The average fresh weight produced by a non-Si pot at a 40.0% reduced rate of N&P was 33.0% heavier than the corresponding tests at a 60.0% reduced rate of N&P.

The average dry weight by a non-Si pot at a 40.0% reduced rate of N&P was 15.0% heavier than the corresponding tests at a 60.0% reduced rate of N&P.

As with all the preceding fertiliser reduction tests the Si-rich compounds produced a greater crop yield than the non-Si protocols. The longest stalk produced by a Si-rich compound at a 60.0% reduced rate of N&P was 45.0 cm which was only 2.0 cm longer than the longest non-Si protocol at a 60.0% reduced rate of N&P, which was lime at 2.0 t/ha. The average stalk length of the Si and non-Si protocols were identical. However, Si-rich compounds produced roots that were, on average, 47.0% longer than the non-Si compounds. This corresponded to the Si-rich compounds producing a total plant that was, on average, 16.0% longer than the non-Si protocols.

The lightest fresh weight produced by a Si-rich compound was 35.0 grams for Compound-B at 1.0 t p/ha. The heaviest fresh weight non-Si compound was lime at 2.0 t/ha which was 40.0 and 80.0% lighter than the lightest and heaviest Si-rich compound at 60.0% reduced rate of N&P consecutively. On average, the fresh weight for the Si-rich protocols was 56.0% heavier than the average fresh weight for the non-Si protocols. The non-Si protocols at 60.0% reduced N&P produced a lighter dry weight than all the corresponding Si-rich compound protocols. The average dry weight for the Si-rich compounds at 60.0% reduced N&P was 31.0% heavier than the corresponding non-Si protocols.

Data detailing the average length and weight of the plants produced by each Si-rich and non-Si fertiliser protocol in direct comparison to the full application rate of N&P-only is presented in Table 20.

Table 20: *The % increase of the length and weight of the trial plants, grown with a 60% reduction in N and P application, in comparison to N&P only.*

	Stalk Length	**Root Length**	**Total Length**	**Fresh Weight**	**Dry Weight**
	------------ cm ------		---------- g per plant ----------		
N&P Only	100.0	100.0	100.0	100.0	100.0
N, P -60% + Lime 2.0 t/ha	100.0	83.3	94.0	67.5	105.6
N, P -60% + Lime 4.0 t/ha	83.7	79.2	82.1	60.0	72.2
N,P -60%+ Compound-A 1.0 t/ha	81.4	120.8	95.5	92.5	122.2
N,P -60%+ Compound-A 2.0 t/ha	100.0	108.3	103.0	95.0	111.1
N,P -60%+ Compound-B 1.0 t/ha	79.1	116.7	92.5	87.5	111.1

N,P -60%+ Compound-B 2.0 t/ha	104.7	133.3	114.9	97.5	116.7
N,P -60%+ Compound-C 1.0 t/ha	93.0	116.7	101.5	112.5	127.8
N,P -60%+ Compound-C 2 t/ha	95.3	125.0	106.0	105.0	122.2

4.6 Test 5 (third pot trial) – Soil pH and Aluminium Concentration

The third pot trial was designed to determine what effects the Si-rich compounds had on soil pH and the concentration of exchangeable Al in the soil in comparison to the non-Si fertilisers with a particular emphasis on lime. The results showing the effects of the Si-rich and non-Si fertilisers on soil pH, and the concentration of exchangeable Al in the soil is provided in Table 21.

Table 21: *Soil pH and exchangeable Al in the soil*

Protocol	pH	Exchangeable Al
		mg/kg
Control	5.7	1.5
N & P Only	5.2	2.4
N, P + Ca 2.0 t/ha + Al 200.0 µmol	4.5	5.6
N, P + Ca 4.0 t/ha + Al 200.0 µmol	5.1	2.2
N,P + Compound-A 1.0 t/ha + Al 200.0 µmol	5.1	2.6
N,P + Compound-A 2.0 t/ha + Al 200.0 µmol	5.0	2.2
N,P + Compound-B 1.0 t/ha + Al 200.0 µmol	5.2	1.9
N,P + Compound-B 2.0 t/ha + Al 200.0 µmol	5.1	1.7
N,P + Compound-C 1.0 t/ha + Al 200.0 µmol	6.3	<0.2
N,P + Compound-C 2.0 t/ha + Al 200.0 µmol	6.5	<0.2
LSD$_{05}$	0.1	0.1

The application of N&P-only to the control pots decreased soil pH by 0.5 units to 5.2. Lime at 2.0 t/ha reacted to the two applications of Al sulphate at 100.0 µmol each by the soil pH decreasing to 4.5. Lime at 4.0 t/ha kept soil pH at only 0.1 pH units less than N&P-only and 0.6 units above lime at 2.0 t/ha. Compounds A and B at both the lower and higher rates of 1.0 t/ha and 2.0 t/ha kept pH between 5.0 and 5.2. Compound-C at 1.0 t/ha had the second-highest pH at 6.3 and Compound-C at 2.0 t/ha had the highest with a pH of 6.5 which was 1.2 and 1.4 pH unis above lime at 4.0 t/ha respectively. The pH improvement of Compound-C at 1.0 t/ha and 2.0 t/ha equates to a 23.0 and 27.0% improvement above lime at 4.0 t/ha respectively.

The control soil with no added fertiliser inputs had 1.5 mg/kg of exchangeable Al. The addition of N&P-only increased exchangeable Al by 60.0% to 2.4 mg/kg. Following two applications of Al sulphate at 100.0 μmol exchangeable Al increased to 5.6 mg/kg for lime at 2.0 t/ha but decreased to 2.2 mg/kg with 4.0 t/ha of lime. Compound-A at 1.0 t/ha and 2.0 t/ha restricted exchangeable Al to 2.6 and 2.2 mg/kg respectively following the two applications of Al sulphate. Exchangeable Al was 1.9 and 1.7 mg/kg for Compound-B at 1.0 t/ha and 2.0 t/ha respectively. The most effective input for reducing exchangeable Al was Compound-C with both the high rate and low rate having a concentration of less than 0.2 mg/kg. The lowest non-Si pot was lime at 4.0 t/ha with an exchangeable Al concentration of 2.2 mg/kg which was more than 1,000.0% higher than the Compound-C concentrations of exchangeable Al.

The results showing the average length of the stalk, root, and total length of the plants grown with added Al is presented in Figure 30.

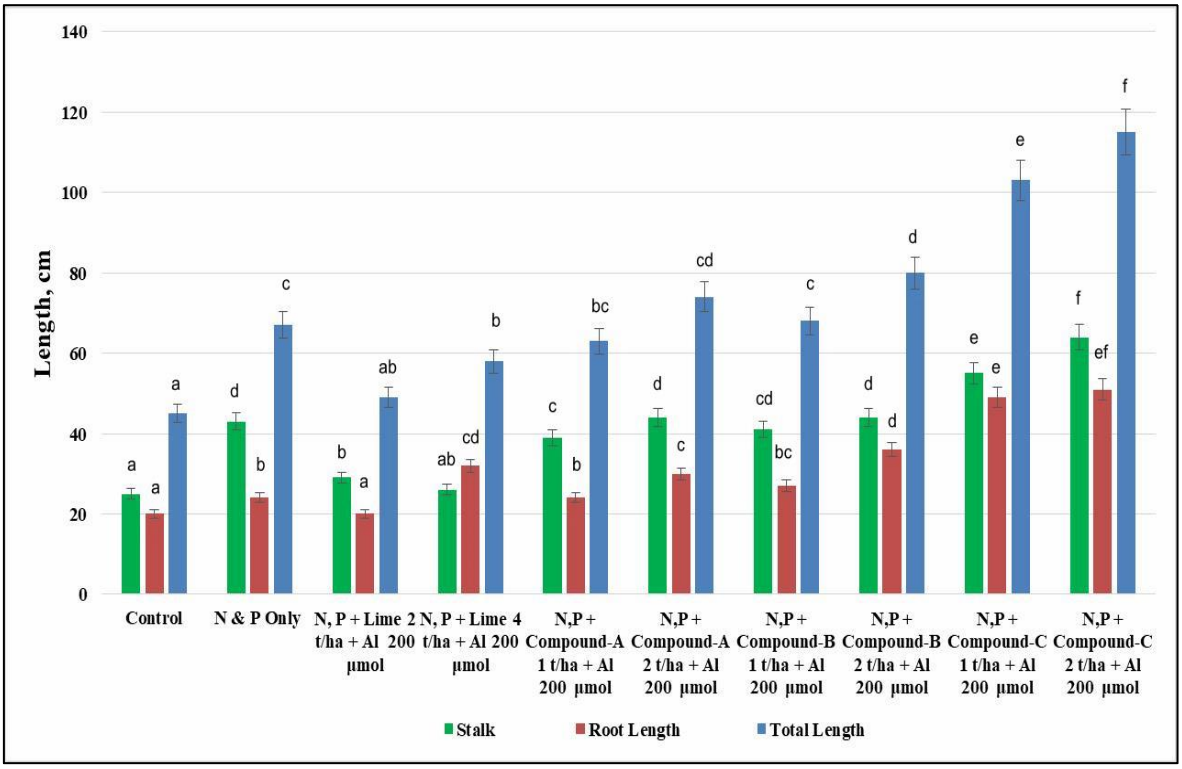


Figure 30: *Average stalk, root, and total plant length of the trial plants grown with added Al. Error bars represent standard deviation at 95% confidence. Letter codes denote significant differences between the control and treatments at 0.05% level.*

Except for both rates of Compound-C the application of Al had a negative effect on crop yield. Lime at 2.0 t/ha was the worst effect of all protocols with a reduction in stem and root length which equated to a reduction in total plant length of 72.0%. Total plant length for lime at 4.0 t/ha was reduced by only 10.0% or from 65.0 to 58.0 cm. Compounds A and B all experienced reductions in total plant length by an average of 4.0%.

The results showing the comparison of the average fresh and dry weight of the plants grown with added Al is presented in Figure 31.

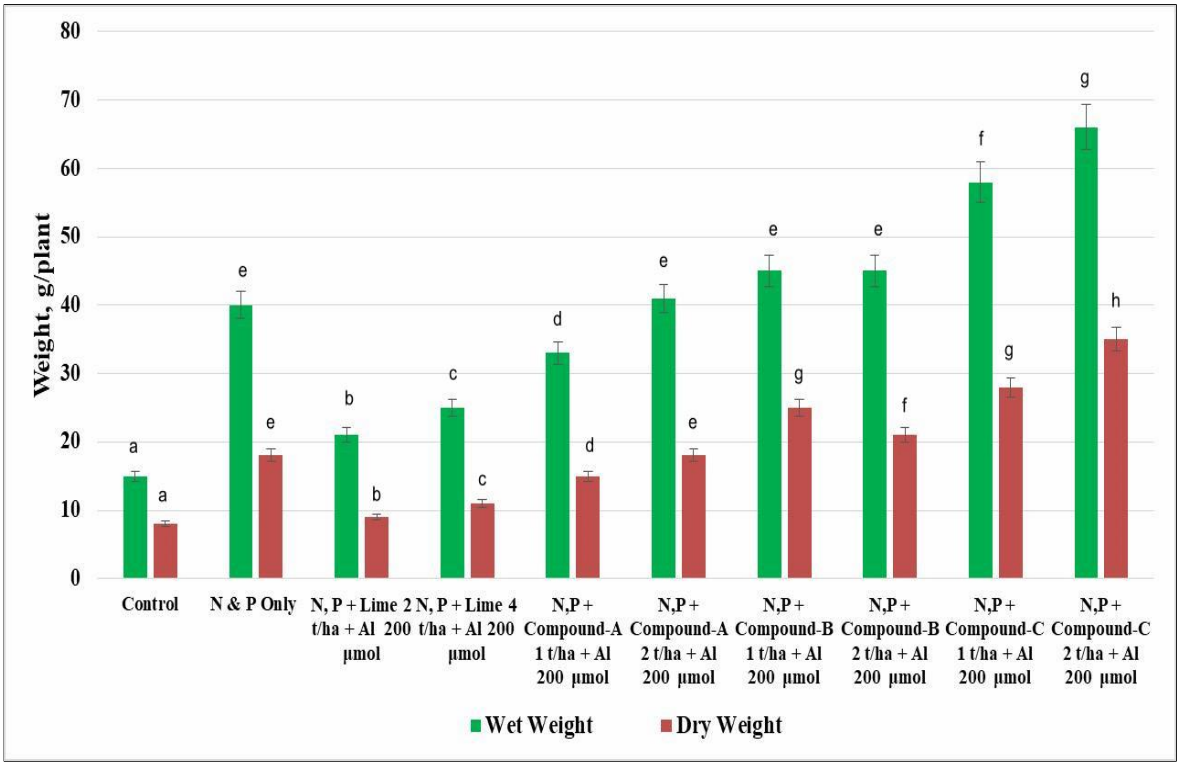


Figure 31: *Average biomass, by fresh and dry weight, of the trial plants grown with added Al. Error bars represent standard deviation at 95% confidence. Letter codes denote significant differences between the control and treatments at 0.05% level.*

The fresh and dry weight of the plant followed a similar pattern to the total plant length. The introduction of Al resulted in a decrease in both fresh and dry weight for both the low and high rates of lime. Lime at 2.0 t/ha was again the most adversely affected with a reduction in fresh and dry weight of 21.0 and 10.0 grams respectively. Lime at 4.0 t/ha had a reduction in fresh and dry weight of 2.0 and 3.0 grams respectively. Compound-A experienced small decreases in fresh in dry weight for both the low and high rate of application. Compound-B at 1.0 t/ha produced the same wet and dry weight as the corresponding non-Al protocols despite a slight reduction in total plant length. Compound-B at the higher rate of 2.0 t/ha experienced a decrease of 4.0 and 2.0 grams for the fresh and dry weight respectively. The lower rate of Compound-C was very similar to its corresponding non-Al protocols with an increase of 2.0 grams and a decrease of 1.0 gram for fresh and dry weight respectively. Compound-C at 2.0 t/ha produced a very slight increase in stalk, root, and total plant length which in turn resulted in a 1.0 gram and 2.0 gram increase in fresh and dry weight respectively.

4.7 Test 6 (fourth pot trial) – Nutrient Concentration and Phosphorus Fixation

The fourth pot trial was designed to determine what effects the Si-rich compounds had on the soil's N and P concentration and the fixation of Pin the soil in comparison to the non-Si fertilisers. The results showing the effects of the Si-rich and non-Si fertilisers on these parameters are provided in Table 22.

Table 22: *N and P concentration in the soil.*

Protocol	Total N	Total P	Olsen P
	%	----------------- mg/kg	-----------------
Control	0.32	508	17
N & P Only	0.22	645	42
N, P + Lime 2.0 t/ha	0.23	718	60
N, P + Lime 4.0 t/ha	0.22	931	71
N,P + Compound-A 1.0 t/ha	0.26	1,465	157
N,P + Compound-A 2.0 t/ha	0.23	1,036	94
N,P + Compound-B 1.0 t/ha	0.27	1,338	166
N,P + Compound-B 2.0 t/ha	0.26	1,447	164
N,P + Compound-C 1.0 t/ha	0.24	1,869	171
N,P + Compound-C 2.0 t/ha	0.20	1,912	166
LSD_{05}	0.1	55	5.5

The application of 300.0 kg/ha of urea and 1,100.0 kg/ha of superphosphate increased total and Olsen P by 137.0 and 25.0 mg/kg respectively. The application of lime at 2.0 t/ha and 4.0 t/ha increased total P by a further 73.0 and 286.0 mg/kg respectively and Olsen P by 18.0 and 29.0 mg/kg respectively.

The same rate of N&P that was applied to the non-Si protocols was also applied to the Si-rich pots and each reduced P fixation in the soil significantly more than the non-Si protocols. The smallest concentration of Olsen P was found with Compound-A at 2.0 t/ha at 94.0 mg/kg which was 32.0% more than the highest concentration found with non-Si protocols. The highest concentration of Olsen P was produced by Compound-C at 1.0 t/ha, which at 171.0 mg/kg, is a 307.0% higher concentration than N&P-only, 185.0% higher concentration than lime at 2.0 t/ha, and 140.0% higher concentration than lime at 4.0 t/ha.

Total P increased sequentially with each higher concentration and volume of Si in the Si-rich compounds except for Compound-A where the 1.0 t/ha volume produced a higher concentration than the 2.0 t/ha volume. The lowest concentration of total P among the Si-rich compounds was produced by Compound-A at 2.0 t/ha, which at 1,036.0 mg/kg, is 11.0% higher than lime at 4.0 t/ha which is the highest concentration of total P produced by a non-Si protocol. The highest concentration of total P among the Si-rich compounds was produced by Compound-C at 2.0 t/ha, which at 1,912.0 mg/kg is 105.0% higher than lime at 4.0 t/ha.

4.8 Test 7 (column experiment) – Nitrogen and Phosphorus Leaching

The column experiment was designed to determine what effects the Si-rich compounds had on the leaching of N and P applied to the soil as fertiliser. The application of 300.0 kg/ha of urea and 1,100.0 kg/ha of superphosphate increased the leaching of nutrients. The results showing the volume of ammonium N (HN4+) and nitrate-N (NO3-) in the leachate is provided in Figures 32 and 33 respectively.

Over a period of 24.0-hours, the Control group of columns went from an average of 38.0 to 3.5 ppm of ammonium N in the leachate. Over the same period, N&P-only went from an average of 92.0 ppm to 45.0 ppm which amounts to a decrease of 51.0%. Lime at 2.0 t/ha and 4.0 t/ha went from 87.0 to 43.0 ppm and 85.0 to 40.0 ppm respectively which equated to a decrease in the volume of leaching by 50.0 and 52.0% respectively. Neither the low nor high rate of lime made any significant improvement to the volume of N&P leached in comparison to N&P-only

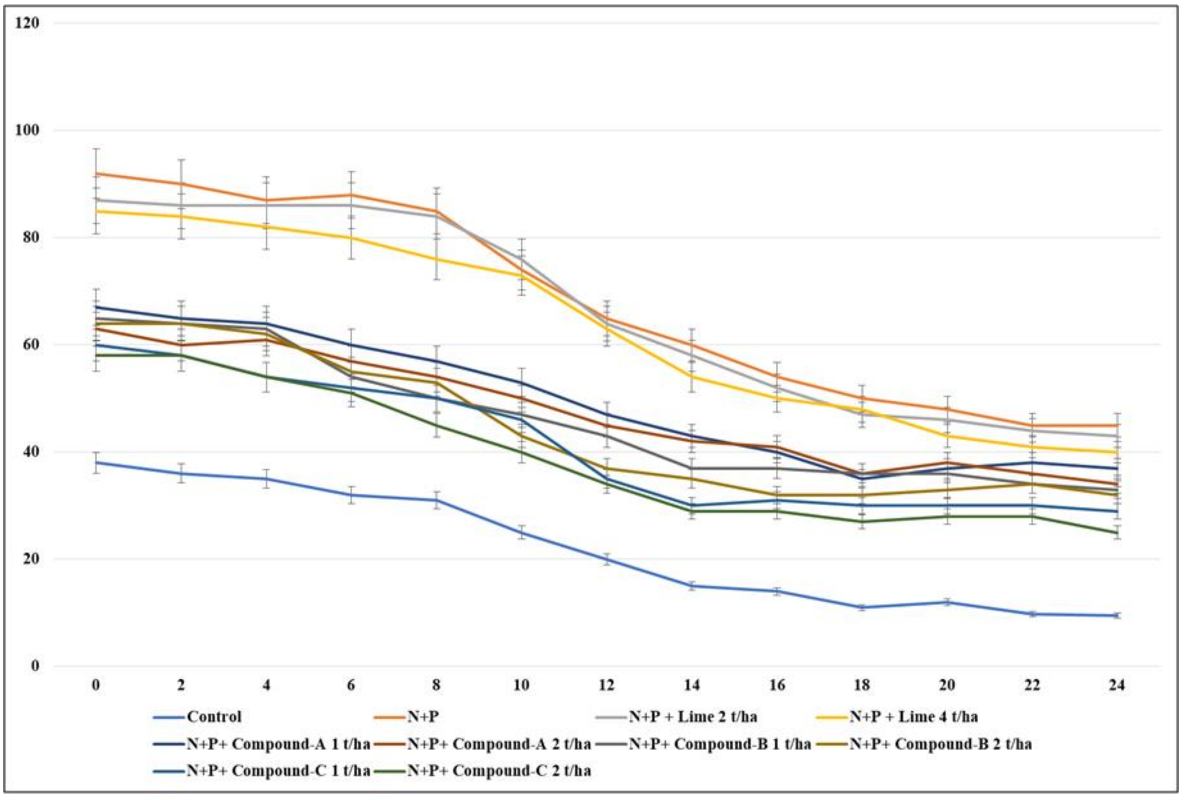


Figure 32: *Ammonium N content in the leachate solution, ppm. Error bars represent standard deviation at 95% confidence.*

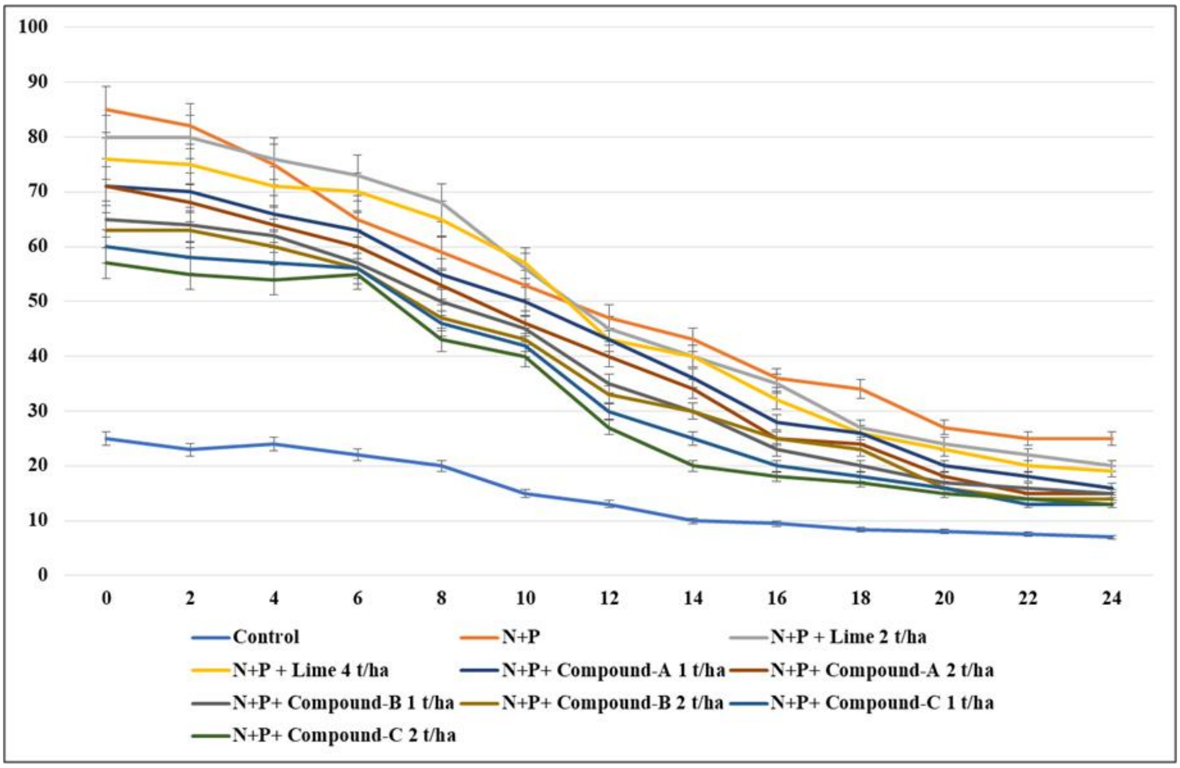


Figure 33: *Nitrate N content in the leachate solution, ppm. Error bars represent standard deviation at 95% confidence.*

After 18.0 hours, Compound-A at 1.0 t/ha had reduced the volume of leaching below that produced by N&P-only and lime at 2.0 and 4.0 t/ha after 24.0-hours. The volume of leached ammonium N had reduced from 63.0 ppm to 34.0 ppm over 24.0-hours for Compound-A at 2.0 t/ha which was only 3.0 ppm or 8.0% less leaching than the same compound at half the application rate. Compound-B at 1.0 and 2.0 t/ha reduced leaching further but only by 10.0 and 5.0% for the corresponding experiments of Compound-A. Compound-C at 1.0 and 2.0 t/ha decreased leaching more than any other trial protocol and by the end of 24.0-hours, the volume of ammonium N in the leachate had been reduced to 29.0 ppm and 25.0 ppm respectively. The worst performing Si-rich compound was Compound-A at 1.0 t/ha but it reduced the volume of ammonium N in the leachate by a further 17.0, 15.0, and 7.5% in comparison to N&P-only, lime at 2.0 t/ha, and lime at 4.0 t/ha. The best performing Si-rich compound was Compound-C at 2.0 t/ha which reduced ammonium N in the leachate by a further 44.0, 41.0, and 37.0% in comparison to N&P-only, lime at 2.0 t/ha, and lime at 4.0 t/ha. In total, Compound-C reduced the volume of ammonium N in the leachate from 92.0 ppm to 25.0 ppm which equates to a 72.0% reduction.

Over a period of 24.0-hours, the Control group of columns went from an average of 25.0 to 7.0 ppm of nitrate-N in the leachate. Over the same period, N&P-only went from an average of 85.0 ppm to 25.0 ppm which amounts to a decrease of 75.0%. Lime at 2.0 t/ha and 4.0 t/ha both reduced the volume of nitrate-N to 20.0 and 19.0 ppm respectively.

There was only a very slight difference between Compounds A and B with the 1.0 t/ha rates reducing the volume of leached nitrate N to 16.0 and 15.0 ppm respectively, and the 2.0 t/ha rates reducing the volume to 15.0 and 14.0 ppm respectively. Both the low and high rates of Compound-C produced the same results with the volume of nitrate-nitrogen, which being 13.0 ppm equates to a total reduction of 85.0% from the N&P-only application levels.

The results showing the volume of Pin the leachate is provided in Figure 34.

Over a period of 24.0-hours, the Control group of columns went from an average of 25.0 to 6.3 ppm of Pin the leachate solution. The application of N&P-only fertiliser increased the volume of Pin the leachate from 25.0 to 75.0 ppm within the first 2.0-hours. However, the reduction of P leaching increased significantly over the

24.0-hours to 9.9 ppm which equated to a reduction of 86.0%. The addition of lime at 2.0 t/ha and 4.0 t/ha had a dramatic effect on P leaching. The immediate volume of P reduced from the N&P-only level of 75.0 ppm to 34.0 and 20.4 ppm respectively and over the period of 24.0-hours reduced it further to 2.6 and 1.1 ppm.

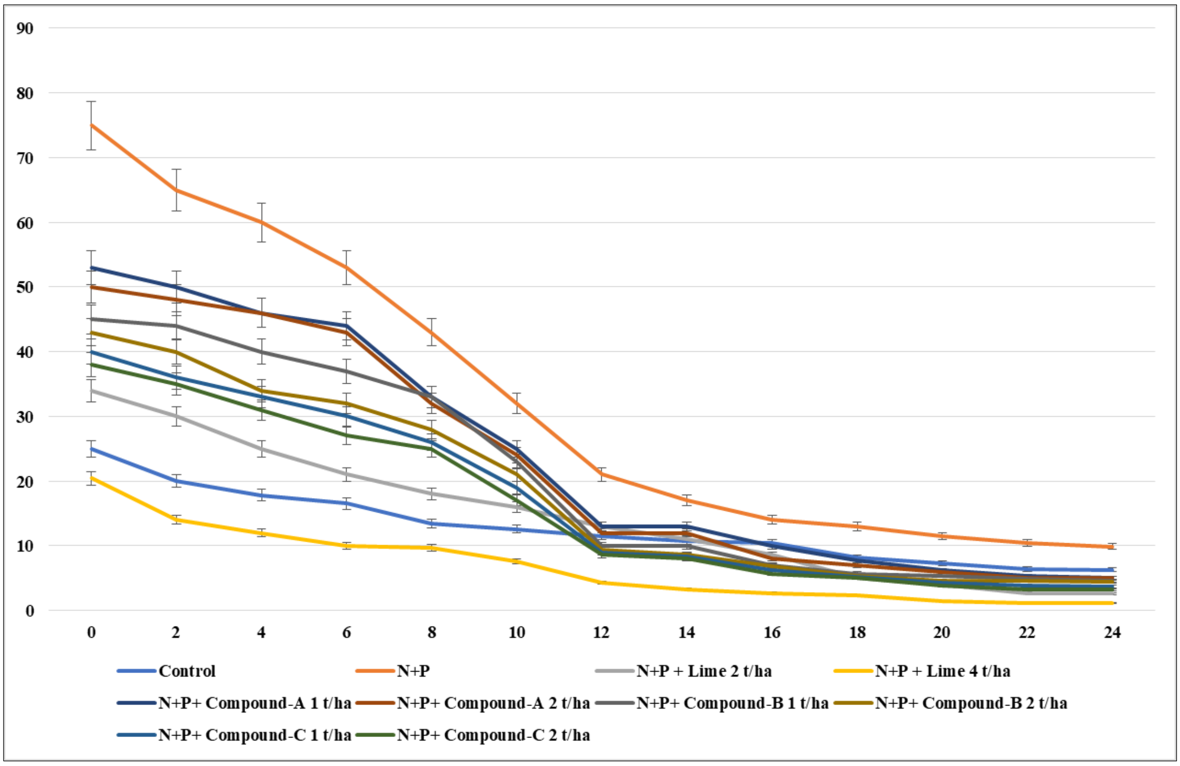


Figure 34: *P in the leachate solution, ppm. Error bars represent standard deviation at 95% confidence.*

While the Si-rich compounds A and B had a dramatic effect on the volume of P found in the leachate, the volumes of 5.0 and 4.6 ppm for the 1.0 t/ha compounds and 5.0 and 4.5 ppm for the 2.0 t/ha compounds did not match the reduction outcomes of lime at both the low and high rates of application. Compound-C was the most effective of the Si-rich compounds, but at 3.7 and 3.2 ppm, they were not as effective as lime at the 1.0 or 2.0 t/ha.

The concentration of total P, Olsen P, water-extractable ammonium N, and water-extractable nitrate N that was in the soil at the conclusion of the column experiment is presented in Table 23.

The application of 300.0 kg/ha of urea and 1,100.0 kg/ha of superphosphate to a soil that experienced intense water movement through the soil profile resulted in a significant loss of N and P from the soil in comparison to the natural water movement of Test 5.

Table 23: *Concentration of N and P in the soil after 24-hour column leaching experiment.*

	Ammonium-N Water Extractable	Nitrate-N Water Extractable	Total P	Olsen P
Control	9.2	10.4	543	15.3
N & P Only	44.0	34.6	667	39.6
N, P + Lime 2.0 t/ha	43.4	35.0	663	14.4
N, P + Lime 4.0 t/ha	44.3	36.4	673	12.5
N,P + Compound-A 1.0 t/ha	46.4	38.3	648	43.0
N,P + Compound-A 2.0 t/ha	47.3	42.5	643	45.3
N,P + Compound-B 1.0 t/ha	47.8	40.4	654	42.4
N, P + Compound-B 2.0 t/ha	48.2	45.6	655	48.5
N, P + Compound-C 1.0 t/ha	47.3	44.1	649	45.6
N, P + Compound-C 2.0 t/ha	49.5	47.1	645	54.7

Comparisons between the different protocols used in the column leaching experiment showed that N&P-only increased ammonium and nitrate N from 9.2 and 10.4 mg/kg to 44.0 and 334.6 mg/kg respectively. Lime at 2.0 and 4.0 t/ha made very little change to the concentration of ammonium and nitrate N. The Si-rich compounds had a greater effect at holding both forms of N in the soil with all three compounds, at both the low rate and high rate of application, having a greater concentration of ammonium and nitrate N than both rates of lime. The best performing Si-rich compound was Compound-C at 2.0 t/ha which increased both forms of N by an additional 12.5 and 36.0% consecutively above N&P-only.

Total and Olsen P increased from the Control volumes of 543.0 and 15.3 mg/kg to 667.0 and 39.6 mg/kg consecutively after the application of N&P-only. The application of lime at 2.0 t/ha decreased total P by 4.0 mg/kg and decreased Olsen P by 25.2 mg/kg. Lime at 4.0 t/ha increased total P by 6.0 mg/kg and significantly reduced Olsen P by 27.1 mg/kg to 12.5 mg/kg. Every Si-rich compound at each rate reduced total P and increased Olsen P concentrations in the soil. Compound-A at 1.0 t/ha reduced total P to 648.0 mg/kg and increased Olsen P to 43.0 mg/kg which equates to a total P decrease of 2.8% and an Olsen P increase of 8.5%. Compound-C at 2.0 t/ha decreased total P to 645.0 mg/kg and increased Olsen P to 54.7 mg/kg which equates to a total P decrease of 4.0% and an Olsen P increase of 38.0%.

The same rate of N&P that was applied to the non-Si pots was also applied to the Si-rich pots and each reduced P fixation in the soil significantly more than the non-Si protocols. The smallest concentration of Olsen P was found with Compound-A at 2.0 t/ha at 94.0 mg/kg which was 32.0% more than the highest concentration found with non-Si protocols. The highest concentration of Olsen P was produced by Compound-C at 1.0 t/ha, which at 171.0 mg/kg, is a 307.0% higher concentration than N&P-only, 185.0% higher concentration than lime at 2.0 t/ha, and 140.0% higher concentration than lime at 4.0 t/ha. Total P increased sequentially with each higher concentration and volume of Si in the Si-rich compounds except for Compound-A where the 1.0 t/ha volume produced a higher concentration than the 2.0 t/ha volume. The lowest concentration of total P among the Si-rich compounds was produced by Compound-A at 2.0 t/ha, which at 1.03 mg/kg, is 11.0% higher than lime at 4.0 t/ha which is the highest concentration of total P produced by a non-Si pot. The highest concentration of total P among the Si-rich compounds was produced by Compound-C at 2.0 t/ha, which at 1,912.0 mg/kg is 105.0% higher than lime at 4.0 t/ha.

CHAPTER 5

Discussion

5.1 Introduction

The overarching objective of this study is to develop a strategy to mitigate the leaching of nutrients that have been applied to farmland as fertilisers. The strategy is required to meet the aspirations of Māori landowners and in that respect, it had to be compatible with the principles and values of kaitiakitanga and had to maintain, if not improve, the economic outcomes of the farming enterprise (Dewes et al., 2011; Phillips et al., 2016). Based on the results of this study a nutrient leaching mitigation strategy that meets the aspirations of Māori landowners was demonstrated. The Si-rich compounds used in this study showed compatibility with the principles and values of kaitiakitanga and the ability to improve the economic outcomes of a farming enterprise.

A gap exists within the existing framework of nutrient leaching mitigation practices, which are currently used and most frequently promoted within the agricultural industry, which would facilitate Māori landowner aspirations. A report authored by McDowell (2013) on behalf of the Ministry for the Environment, identified and assessed over fifty nutrient leaching mitigation practices that have been used in New Zealand. The report states that in general, the strategies have three main problems that inhibit their uptake and overall effectiveness. These problems would make them incompatible with the aspirations of Māori landowners, they being:

1. Cost - the cost to implement and use the strategies.
2. Time - the length of time it takes for the strategies to work.
3. Harm - the environmental harm that the strategies can cause.

Cost - In addition to the general cost of implementing and utilising the strategies being restrictive to widespread use, the report states that in general, the least expensive strategies are the least effective and the most expensive strategies are the most effective(McDowell et al., 2013). Therefore, the most effective nutrient leaching practices are beyond the reach of many landowners because of the cost. With the lack of access to capital having been identified as a significant and disproportionate problem for Māori landowners (ANZ Bank, 2014; Phillips et al., 2014), this would make the best strategies disproportionately unavailable to Māori landowners. Further, if hard-earned capital is spent on a less effective mitigation practice because it is the only practice that is affordable this may lead to unfulfilled kaitiakitanga aspirations and questionable financial management. Also, kaitiakitanga requires the protection of all aspects of the environment including those that provide for the economic well-being of Māori (Morgan, 2008). Therefore, in order to align with the principles and values of kaitiakitanga, a mitigation practice must incorporate economic well-being. The general restrictive cost of the mitigation practices, and the expense of the most effective mitigation practices coupled with the disproportionate lack of capital available to Māori, do not fit within a reasonable description of economic well-being for Māori. Therefore, the economic incompatibility of the existing mitigation framework with the aspirations of Māori landowners is threefold:

1. The restrictive cost to implement and utilise the mitigation practices.
2. The disproportional lack of access to capital and therefore the most effective mitigation practices.
3. The economic well-being of Māori that is required by kaitiakitanga.

Time - the fact that it can take decades for some of the identified mitigation practices to achieve their outcomes also makes them less than ideal for Māori who are determined to fulfil their guardianship responsibilities as kaitiaki (Marsden & Henare, 1992). The notion of guardianship and protection is one of immediacy and efficiency. The values of kaitiakitanga place reciprocal responsibilities on landowners wherein the immediate benefits provided by the environment must be immediately reciprocated with guardianship. Neither the notion of guardianship nor reciprocal responsibilities are compatible with protracted environmental strategies. The mana of Māori as kaitiaki is partially dependent on maximal effort in protecting and restoring the mauri of the environment (Department of Conservation, 1994). In no way do the responsibilities of the kaitiaki toward Papatūānuku involve being passive or less than effective; maximal effort denotes vigour, action, output, and even force. The use of ineffective and protracted practices is not only counter to the maximal effort aspect of kaitiakitanga but also the aspect of economic well-being as it relates to cost-effectiveness and the wise use of hard-earned capital. Therefore, the incompatibility of the existing mitigation framework with the aspirations of Māori landowners as it relates to time is threefold:

1. The immediacy and efficiency of guardianship and the principle of reciprocity.
2. The maximal effort required of Māori as kaitiaki.
3. The economic well-being of Māori required by kaitiakitanga.

Harm – any action that would bring harm to the environment or diminish its mauri is the very antithesis of kaitiakitanga (Kawharu, 2010; Tomas, 2011). Environmental trade-offs, as would be necessary for any mitigation practice that reduced leaching while causing harm in another part of the environment, are difficult to justify due to the very nature of mauri. Any form of harm to any aspect of the environment results in a depletion or shift in mauri in that aspect of the environment. However, the shift in mauri is not contained or localised to that aspect of the environment, there is a domino effect. Any shift in mauri in one aspect of the environment produces a reaction, or a shift in mauri, in the next most closely related aspect of the environment. This reaction continues to the next most closely related aspect of the environment and then the next until, like falling dominos, the mauri of the entire ecosystem has shifted (Harmsworth & Awatere, 2013). Due to the domino shift in mauri, any benefit gained from a reduction in nutrient leaching will be negated by a shift in mauri across the entire environment. Finally, the domino shift in mauri has the potential to harm the economic well-being of the landowners by impacting the aspects of the environment that are related to economic well-being. Therefore, the harm caused by the existing mitigation framework is incompatible with the aspirations of Māori landowners on three grounds:

1. The antithesis of harm to the values and principles of kaitiakitanga.
2. The domino effect of environmental harm on mauri.
3. The potential for harm to the economic well-being of Māori.

The study's leaching mitigation strategy can fill the gap in the leaching mitigation practices that are currently used and promoted in New Zealand with the systematic use of Si-rich compounds.

The current literature indicates that Si-rich compounds can affect various agricultural and environmental features of a farming system. For example, Si-rich compounds can increase crop yield, regulate soil pH, improve nutrient efficiency, and reduce nutrient leaching. Typically, the literature investigates the effects of Si-rich compounds on a single feature of an agricultural system (e.g. crop yield), sometimes two features simultaneously (e.g. crop yield + soil pH concurrently), and perhaps even three features (e.g. crop yield + soil pH + nutrient efficiency concurrently). Where this study's research is unique is that it investigates all the simultaneous effects of Si-rich compounds on all the agricultural features that are required for the nutrient leaching mitigation strategy to meet the aspirations of Māori landowners and for the objective of this study to be achieved. There are a total of eight simultaneous agricultural features that are investigated by this study, they being:

1. Crop yield with a full rate of N and P fertilisers.
2. Crop yield with reduced rates of N and P fertilisers.
3. Crop yield and the regulation of soil pH.
4. Crop yield and the reduction of Al toxicity.
5. N concentration in the soil under natural water flow.
6. P concentration in the soil under natural water flow.
7. Fertiliser efficiency
8. Soil P fixation.

The study also investigates a total of four simultaneous environmental features that are required of the nutrient leaching mitigation strategy to meet the aspirations of Māori landowners and for the objective of this study to be achieved, they are:

1. N concentration in leachate (N leaching).
2. P concentration in leachate (P leaching).
3. N concentration in the soil under artificial water flow.
4. P concentration in the soil under water artificial water flow.

Pot trials, column leaching experiments, and soil and chemical analysis are standard and commonly used methods to examine agricultural and environmental practices and outcomes. The investigation of the effects of the Si-rich compounds on the eight agricultural and four environmental features related to this study were conducted using these standard methods. The eight agricultural features were investigated using a series of pot tests and the four environmental features were investigated using column leaching tests. Both the agricultural and environmental features used soil and chemical analysis, with the addition of economic analysis. This final chapter discusses and evaluates the results from the investigation and determines if the objectives of the study were achieved. This chapter has a strong emphasis on economic outcomes because it doesn’t matter how effective the Si-rich compounds are in an agricultural or environmental context if the leaching mitigation strategy is not economically viable and does not meet the economic aspirations of Māori landowners.

5.2 Silicon Mineral Analysis

The current literature indicates that while Si fertilisers can contribute to higher crop yields, improved crop quality, lower input costs, and reduce some of the negative impacts that agriculture can have on the environment some types of Si fertilisers can also simultaneously cause environmental damage in other areas (Liang et al., 2015a). The current literature indicates that unlike industrial by-product derived Si fertilisers, naturally occurring silicate minerals can produce positive agricultural and environmental outcomes without causing any harm to the environment (Etesami & Jeong, 2018; Liang et al., 2015b; Matichenkov, 2019; Ning et al., 2014). However, while natural silicate minerals such as zeolite, diatomaceous earth, and bentonite are ecologically friendly sources of Si they typically require an application of anywhere from 4.0 to 10.0 tonnes per hectare to be effective (Kulikova, 2012; Matichenkov et al., 2005). While this application rate would likely reduce nutrient leaching from farmland in a volume that would achieve the environmental objectives of this study it would likely not meet the economic objectives.

The current literature indicates that the effectiveness of Si-rich compounds in agricultural and environmental contexts depends largely on the biogeochemical activity and the content of plant-available Si in the compound (Ma & Takahashi, 2002; Matichenkov & Bocharnikova, 1994). The required rate of application to achieve agricultural and environmental outcomes is also determined by the content of plant-available Si (Bocharnikova & Matichenkov, 2012; Ma & Takahashi, 2002).

A test was conducted on five naturally occurring silicate minerals to determine which of them would be the most suitable to be treated with concentrated monosilicic acid to increase its concentration of plant-available Si. The SEM analysis showed that Compound-B had the smallest particle size, largest surface area, and most complex physical structure. These factors made Compound-B the best compound to be treated with concentrated monosilicic acid. Even though zeolite and Compound-A had a higher content of SiO2, at 74.0 and 73.0% consecutively than the 68.2% SiO2 content of Compound-B, with which to react with the concentrated monosilicic acid, the smaller particle size and larger surface area of Compound-B outweighed the small difference in SiO2 content. After activating Compound-B and creating Compound-C all six compounds were tested to determine their concentration of active-Si using the methodology described in the Materials and Methods section of this thesis.

Testing for active-Si provides a highly accurate measure of the concentration of plant-available Si in the Si-rich compound (Bocharnikova & Matichenkov, 2012). Using the traditional method of analysing dried solid samples to determine Si content, as described by the National Agriculture and Food Research Organization (NIAES) in the Official Methods of Analysis of Fertilizers (NIAES, 1987), does not give an as accurate determination of plant-available Si as the method to test for active-Si. When following the NIAES method, a solid sample is dried in preparation for analysis. Drying the sample reduces the concentration of monosilicic and polysilicic acids due to the adsorption of the soluble Si substances from the sample surface and the subsequent dehydration and formation of amorphous silica films (Matychenkov & Snyder, 1996). When water is added to a dry sample, Si passes into solution as monosilicic acid. However, the Si concentration that is measured includes both the monosilicic (plant-available) and polysilicic (plant-unavailable) acids (Nonaka & Takahashi, 1988). Also, the use of a water extraction derived from a dried solid sample requires a 2 to 3 week incubation period for the natural equilibrium, between the solid phases of Si-rich compounds and the soluble form of Si in the liquid phase, to be restored (NIAES, 1987).

Due to the problems associated with dried samples, an analysis methodology using fresh samples of Si-rich materials has been developed (Bocharnikova & Matichenkov, 2012; Matichenkov, 2007; Matychenkov & Snyder, 1996). The concentration of monosilicic acid in the fresh sample shows the actual concentration of plant-available Si. However, a water extraction of the fresh sample does not reveal the total amount of Si that can be absorbed by a plant over time. Therefore, an acid extraction is used which will measure the amorphous form of Si which controls the solubility of Si in the soil (Barsykova & Rochev, 1979; Matychenkov & Ammosova, 1996; NIAES, 1987). This form of extraction measures the concentration of Si that can readily pass into solution and be adsorbed by plants over time. The combination of water-extractable Si (actual Si), using samples taken after 1.0-day of incubation and again at 4.0-days of incubation, and acid extractable Si (potential Si) provides a highly accurate measure of the Si status and this status is known as Active-Si (Bocharnikova & Matichenkov, 2012; Matichenkov, 2007). A summary of the Si analysis methodology measurements is provided in Figure 35.

Dry Samples

- Reduced concentration of monosilicic and polysilicic acids.
- Measures both plant-available and plant-unavailable concentrations of silicon.
- Disburbed equilibrium between the solid and liquid phases of of silicon.
- Measurement of plant-available and plant-unavailable silicon

Fresh Samples

- **Water Analysis** - Concentration of immediately plant-available silicon.
- Mesurement of *Actual* plant-available silicon
- **Acid Analysis** - Concentration of silicon that can pass into solution and be taken up by plants over time.
- Measure ment of *Potential* plant-available silicon

Active Silicon = 10 x (Actual silicon $_{1\ day}$ + Actual silicon $_{4\ day}$) + Potential silicon

Figure 35: *Measurements of Si analysis Source: (Bocharnikova et al., 2011)*

The creation of Compound-C provides a methodology that can be followed by anyone who wants to increase the efficiency of a Si-rich compound. Understanding the physical and chemical composition of the Si-rich compound (Compound-B) before and after it was activated also helps us understand the potential increase in efficiency that can be obtained from activating a Si-rich compound with concentrated monosilicic acid.

Following the active-Si analysis, three Si-rich compounds were selected for use in this study's trials and experiments. A Si-rich compound with a low concentration of active-Si, a medium concentration, and a high concentration were selected and are referred to in this study as Compound-A, Compound-B, and Compound-C.

The naturally occurring silicates that were selected were named Compounds A, B, and C to avoid confusion between them and other naturally occurring silicates of the same name and to ensure that the type of silicate cannot be recognised as having the ability to replicate the results of this study. For example, there are at least six different zeolite products that are commercially available in New Zealand. Each of these six different products has different physical and chemical properties, including different concentrations of Si. It would therefore be a mistake to assume that any zeolite product will replicate the agricultural and environmental outcomes of any other zeolite product. The same would be true for all the different types of silicate materials. The single most important factor concerning the Si-rich compounds, as it relates to the replicability of results, is the concentration of active-Si. If the results of this study are to be replicated the type of product has no relevance.

With the completion of the active-Si analysis and the selection of the Si-rich compounds, the pot trials and column leaching experiments could be conducted and the suitability of the Si-rich compounds at achieving the objectives of this study could be determined.

5.3 Alignment with Kaitiakitanga

The leaching mitigation strategy, and therefore the use of Si-rich compounds, must align with the principles and values of kaitiakitanga for the objective of this study to be achieved. The current literature indicates that the use of Si-rich compounds by pre-European Māori was a standard feature of horticultural practice as it was for early post-European agricultural practice (Burtenshaw, 2010; Roskruge, 2011). From this perspective, it can be determined that, in principle, the use of Si-rich compounds is a culturally acceptable practice. However, the types of Si-rich compounds used today are not the same as the phytoliths used by early Māori. The current literature indicates that some Si-rich compounds commonly used in agriculture today can contain heavy metals and act as a source of contamination (Gascho, 2001). Regardless of some contemporary Māori attitudes toward applying fertilisers that contain heavy metals to farmland, and therefore potentially to natural waters through leaching, it is not a practice that is aligned to the traditional principles and values of kaitiakitanga (Reid et al., 2013).

Si-rich compounds such as zeolite, bentonite, and diatomaceous earth are naturally occurring silicate minerals. However, heavy metals are naturally occurring elements (Kaur et al., 2019) so being naturally occurring is in itself, no guarantee of alignment with the principles and values of kaitiakitanga. Further, Si is not found in a free form in nature, it is only found bonded to other elements and can be found in compounds that contain heavy metals (Greenwood & Earnshaw, 2012). Due to their high degree of toxicity the heavy metals cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg) and the metalloid arsenic (As) are considered the priority inorganic pollutants concerning the environment and human health (Tchounwou et al., 2012). According to the manufacturer, Compound-B contains 0.003% inorganic pollutants and if it contains As, Cd, Cr, and Pb it does so at less than the detectable limits of a licenced and fully certified analytical laboratory. No data concerning the heavy metal content for Compound-A is available.

The element Si, and all its natural forms, including silica and silicates, is inherently non-toxic (Martin, 2007). If Si is found in any compound that does not have toxic concentrations of any element, such as compounds B and C, then it is compatible with kaitiakitanga. However, before the leaching mitigation strategy can be considered fully aligned with kaitiakitanga, the economic viability and the efficacy of its agricultural and environmental effects must also demonstrate compatibility.

5.4 Crop Yield

The use of the leaching mitigation strategy has a monetary cost that will require ongoing capital investment. Access to capital has been identified as a major limiting feature of Māori agricultural operations and their ability to expand and improve profitability (Price Waterhouse Coopers, 2013; Cortés-Acosta, 2019; Phillips et al., 2016). The profitability of a crop growing agricultural operation is based to a large degree on the size of the crop yield relative to the economic cost of obtaining that yield. From an environmental perspective, success or failure can be measured by the amount of environmental damage caused in obtaining that yield. The assessment that the GR was a failure because of the environmental damage it caused, despite any other benefits or achievements, including increased crop yield (Zimdahl, 2012), is aligned with the broader view required by kaitiakitanga of mankind's inseparability from the environment (Harmsworth & Awatere, 2013). With the objective of developing a strategy that meets both the economic and environmental aspirations of landowners, the use of the strategy can be justified if it can increase crop yield at least enough to cover the economic cost of doing so.

Trial One was conducted to compare the crop yield and the cost to obtain that yield with different fertiliser protocols that included the selected Si-rich compounds. The yield data was provided in the Results section of this thesis, the economic data is provided in Table 24.

Table 24: *Economics of the trial plant yields in comparison to N&P-only*

Protocol	Inputs Cost per ha	Fresh Weight Yield	Fresh Weight Yield Cost	Cost per Unit of Fresh Weight	% Increase in Units
N & P Only	$648.00	40	$16.20	$0.41	0.0%
N, P + Lime 2 t/ha	$720.40	42	$17.15	$0.41	5.0%
N, P + Lime 4 t/ha	$792.80	27	$29.36	$1.09	-32.5%
N,P + Compound-A 1 t/ha	$828.00	45	$18.40	$0.41	12.5%
N,P + Compound-A 2 t/ha	$1,008.00	43	$23.44	$0.55	7.5%
N,P + Compound-B 1 t/ha	$868.00	45	$19.29	$0.43	12.5%
N,P + Compound-B 2 t/ha	$1,088.00	49	$22.20	$0.45	22.5%
N,P + Compound-C 1 t/ha	$878.00	56	$15.68	$0.28	40.0%
N,P + Compound-C 2 t/ha	$1,108.00	65	$17.05	$0.26	62.5%

The economic results, in general, paralleled the yield results with the Si-rich compounds proving to be the most economically profitable protocols. While the Si-rich protocols were more expensive than the non-Si protocols by an average of 33.0% they produced a much higher yield at a significantly lower cost per unit of yield. The cost per unit of yield is the most effective method for determining which fertiliser protocol was superior from a cost-for-yield perspective. N&P-only and lime at 2.0 t/ha produced each unit of yield weight for 41.0 cents. Lime at 4.0 t/ha was more than double the cost-for-yield at $1.09. At 41.0 cents, the cost-for-yield of Compound-A at 1.0 t/ha was the same as N&P-only and lime at 2.0 t/ha. However, Compound-A at 1.0 t/ha produced 12.5% more units of weight than N&P-only, 7.5% more than lime at 2.0 t/ha, and 45.0% more than lime at 4.0 t/ha, which means that Compound-A at 1.0 t/ha generated more net revenue per hectare of land. Compound-B at 1.0 and 2.0 t/ha were both more expensive on a cost-for-yield basis than N&P only and lime at 1.0 t/ha but it produced more units of weight. Compound-C at 1.0 and 2.0 t/ha were significantly more profitable than any other fertiliser protocol with a cost per unit of weight at 28.0 and 26.0 cents and an increase in units of weight by 40.0 and 62.5% respectively.

The economic viability of utilising Si-rich compounds is evidenced by the increased profitability in comparison to all the non-Si protocols. The efficacy of the Si-rich compounds is shown in the biomass data of Trial One, as presented in the Results section of this thesis, and supported by the corresponding economic data.

One of the goals of this research was to determine if Si-rich compounds could completely replace lime in order to reduce farming costs and free up capital which could then be used to cover the cost of implementing and using the nutrient leaching mitigation strategy. Based on the economic and biomass data from Trial One, Si-rich compounds outperformed lime on every tested parameter. However, economic and biomass data does not necessarily mean that lime can be replaced. The replacement of lime will need to be determined with supporting data from the pot trials that analysed soil pH and Al toxicity. This is due to lime’s primary role being the regulation of soil pH and reducing Al toxicity.

The results from this trial demonstrate both the agricultural effectiveness and economic viability of the Si-rich compounds in producing crop yield. As a stand-alone component of the leaching mitigation strategy, crop yield can be considered aligned with the aspirations of Māori landowners.

5.5 Crop Yield with Reduced Fertiliser Rates

The replacement of lime is only one cost-saving measure to be determined by this study. Fertiliser inputs are the single largest fixed cost for sheep and beef farming at 22.0% of total expenses, and the second largest for dairy farming at 13.0% (Fitzgerald, 2016; Grafton & Manning, 2017). A reduction in the amount of fertiliser applied to agricultural land will have a positive economic impact if production levels can at least be maintained. Also, the single biggest factor in the leaching of N and P fertiliser is the application of these fertilisers in a volume that exceeds the crop's demand for and ability to uptake the nutrients (Liu et al., 2019; Wang & Li, 2019). Therefore, any strategy that can reduce the volume of N and P fertilisers being applied to land can be considered an environmental strategy. The first fertiliser reduction trial grew crops with a fertiliser protocol that had a 20.0% reduction in N and P application. The economic results from this trial are presented in Table 25.

Table 25: *Economics of the trial plant yields with a 20.0% reduction in N and P application, in comparison with N&P-only.*

Protocol	Inputs Cost per ha	Fresh Weight Yield	Fresh Weight Yield Cost	Cost per Unit of Fresh Weight	% Increase in Units
N & P Only	$648.00	40	$16.20	$0.41	0.0%
N, P -20% + Lime 2.0 t/ha	590.80	40	$14.77	$0.37	0.0%
N, P -20% + Lime 4.0 t/ha	663.20	37	$17.92	$0.48	-7.5%
N, P -20% + Compound-A 1.0 t/ha	698.40	49	$14.25	$0.29	22.5%
N, P -20% + Compound-A 2.0 t/ha	878.40	53	$16.57	$0.31	32.5%
N, P -20% + Compound-B 1.0 t/ha	738.40	50	$14.77	$0.30	25.0%
N, P -20% + Compound-B 2 t/ha	958.40	63	$15.21	$0.24	57.5%
N, P -20% + Compound-C 1.0 t/ha	748.40	68	$11.01	$0.16	70.0%
N, P -20% + Compound-C 2.0 t/ha	978.40	75	$13.05	$0.17	87.5%

A 20.0% reduction in fertilisers reduced the cost per unit of fresh weight for both non-Si and Si-rich plants. In comparison to N&P-only, the Si-rich protocols all experienced a percentage increase of weight units over that produced with a full rate of fertiliser. Every economic parameter measured for the 20.0% reduction protocols of the Si-rich compounds was an improvement in comparison to the full rate of fertiliser and was significantly better than the non-Si protocols.

The economic viability of utilising Si-rich compounds increases with a 20.0% reduction in N and P application. The economics are improved not only because of a 20.0% reduction in fertiliser cost but also because of an increase in crop yield and the subsequent decrease in cost-for-yield. The average cost per unit of fresh weight produced by the Si-rich plants was 24.0 cents in caparison to 39.0 cents for the full rate of fertiliser, which equates to a 38.4% decrease in cost. The efficacy of Si-rich compounds with a 20.0% reduction in N and P fertiliser is demonstrated by the increased yield and reduced cost over the full-rate protocol. Therefore, the 20% reduction protocol must be considered as aligned with the aspirations of Māori landowners.

A further reduction in N and P application could improve the economic viability of the leaching mitigation strategy and reduce agricultural expenses. The trial with a fertiliser protocol of a 40.0% reduction in N and P fertilisers was conducted and the economic results are presented in Table 26.

In general, the Si-rich protocols produced their fresh weight yields at a lower cost than the non-Si protocols. The cost per unit of fresh weight was lower and the percentage increase in units was higher for all the Si-rich protocols than the non-Si protocols. Compound-A at both 1.0 and 2.0 t/ha had a lower yield cost but a higher cost per unit of fresh weight than the corresponding tests at a 20.0% reduction in fertiliser. Compounds B and C at both the low and high rates were more expensive on a yield and unit cost basis than its corresponding tests at a 20.0% reduced rate of fertiliser.

The economics of utilising a fertiliser protocol with all three Si-rich compounds and a 40.0% reduction in N and P is not as good as the 20.0% reduction protocol.

However, except for Compound-C, the 40.0% reduction protocol provides better economics than the full-rate protocol and requires a smaller upfront cost than both the no-reduction and 20.0% reduction protocols. Therefore, even though the 40.0% reduction protocols were not as economically effective as the 20.0% protocol its efficacy is nevertheless demonstrated by the increased yield and reduced cost over the full-rate protocol. Therefore, the 40% reduction protocol must be considered as aligned with the aspirations of Māori landowners.

Table 26: *Economics of the trial plant yields with a 40.0% reduction in N and P application, in comparison with N&P-only.*

Protocol	Inputs Cost per ha	Fresh Weight Yield	Fresh Weight Yield Cost	Cost per Unit of Fresh Weight	% Increase in Units
N & P Only	$648.00	40	$16.20	$0.41	0.0%
N, P -40% + Lime 2.0 t/ha	461.20	37	$12.46	$0.34	-7.5%
N, P -40% + Lime 4.0 t/ha	533.60	31	$17.21	$0.56	-22.5%
N, P -40% + Compound-A 1.0 t/ha	568.80	43	$13.23	$0.31	7.5%
N, P -40% + Compound-A 2.0 t/ha	748.80	48	$15.60	$0.33	20.0%
N, P -40% + Compound-B 1.0 t/ha	608.80	48	$12.68	$0.26	20.0%
N, P -40% + Compound-B 2.0 t/ha	828.80	50	$16.58	$0.33	25.0%
N, P -40% + Compound-C 1.0 t/ha	618.80	53	$11.68	$0.22	32.5%
N, P -40% + Compound-C 2.0 t/ha	848.80	54	$15.72	$0.29	35.0%

The final trial for a reduced rate of fertiliser was conducted with a 60.0% reduction in N and P fertiliser. The results from this trial are presented in Table 27.

The yield for the Si-rich compounds at 60.0% less N and P were lower than every other corresponding trial. However, the Si-rich protocols were comparable and in most cases superior to those produced by lime in full-rate, 20.0% reduction and 40.0% reduction tests. Compound-C in particular was superior to lime and produced a larger yield than lime at both rates from all lime protocols and did so with a lower cost per unit of fresh weight. The cost per unit of fresh weight was generally higher for the 60.0% protocols with an average cost of 37.0 cents compared to 29.0 and 25.0 cents for the 20.0 and 40.0% protocols consecutively. Compounds A and B at both the low and high rates had a reduced percentage of units compared to N&P-only, with only Compound-C producing an increase which at an average of an 8.75% increase was significantly less than the corresponding tests at 20.0%, 40.0% and full-rate protocols of 33.8%, 78.8%, and 51.25% consecutively.

Table 27: *Economics of the trial plant yields with a 60.0% reduction in N and P application, in comparison with N&P-only*

Protocol	Inputs Cost per ha	Fresh Weight Yield	Fresh Weight Yield Cost	Cost per Unit of Fresh Weight	% Increase in Units
N & P Only	$648.00	40	$16.20	$0.41	0.0%
N, P -60% + Lime 2.0 t/ha	331.60	27	$12.28	$0.45	-32.5%
N, P -60% + Lime 4.0 t/ha	404.00	24	$16.83	$0.70	-40.0%
N, P -60% + Compound-A 1.0 t/ha	439.20	37	$11.87	$0.32	-7.5%
N, P -60% + Compound-A 2.0 t/ha	619.20	38	$16.29	$0.43	-5.0%
N, P -60% + Compound-B 1.0 t/ha	479.20	35	$13.69	$0.39	-12.5%
N, P -60% + Compound-B 2.0 t/ha	699.20	39	$17.93	$0.46	-2.5%
N, P -60% + Compound-C 1.0 t/ha	489.20	45	$10.87	$0.24	12.5%
N, P -60% + Compound-C 2.0 t/ha	719.20	42	$17.12	$0.41	5.0%

Both the economic and agricultural outcomes cannot justify a 60.0% reduction protocol and therefore cannot be considered suitable as a leaching mitigation strategy or aligned with the responsibilities of kaitiakitanga.

5.6 Soil pH and Aluminium Concentration

The economic viability of the leaching mitigation strategy was based in part on the ability of Si-rich compounds to replace lime. The primary reason for applying lime to agricultural land is to regulate pH and counteract Al toxicity (Li et al., 2019; Morton & Moir, 2018). The current literature indicates that there are five mechanisms that Si has to regulate soil pH and counteract Al toxicity as opposed to the single mechanism of lime (Matichenkov et al., 2020). If these mechanisms can regulate pH and reduce exchangeable Al in the soil as effectively as lime, the Si-rich compounds can replace lime and consequently reduce input costs and improve the economic viability of the leaching strategy. Tests were conducted to determine the effects of the Si-rich compounds on soil pH and the concentration of Al in the soil. The data from the pH and Al tests was presented in the Results section of this thesis.

Soil pH is fundamental in controlling the bioavailability of nutrients to plants and in this way is a yield-limiting factor (Neina, 2019). A very low pH, or highly acidic soil, is not conducive to the efficient plant utilisation of many nutrients including N, P, and K. Likewise, a very high pH, or highly alkaline soil, is also not conducive to the efficient utilisation of nutrients by plants (Kgopa et al., 2014; Neina, 2019). The most effective pH for nutrient availability varies from crop to crop, but generally, soils with a pH of 6.0 to 7.5 are within the optimal pH range. An illustration showing the optimal pH range for the availability of multiple nutrients is presented in Figure 36.

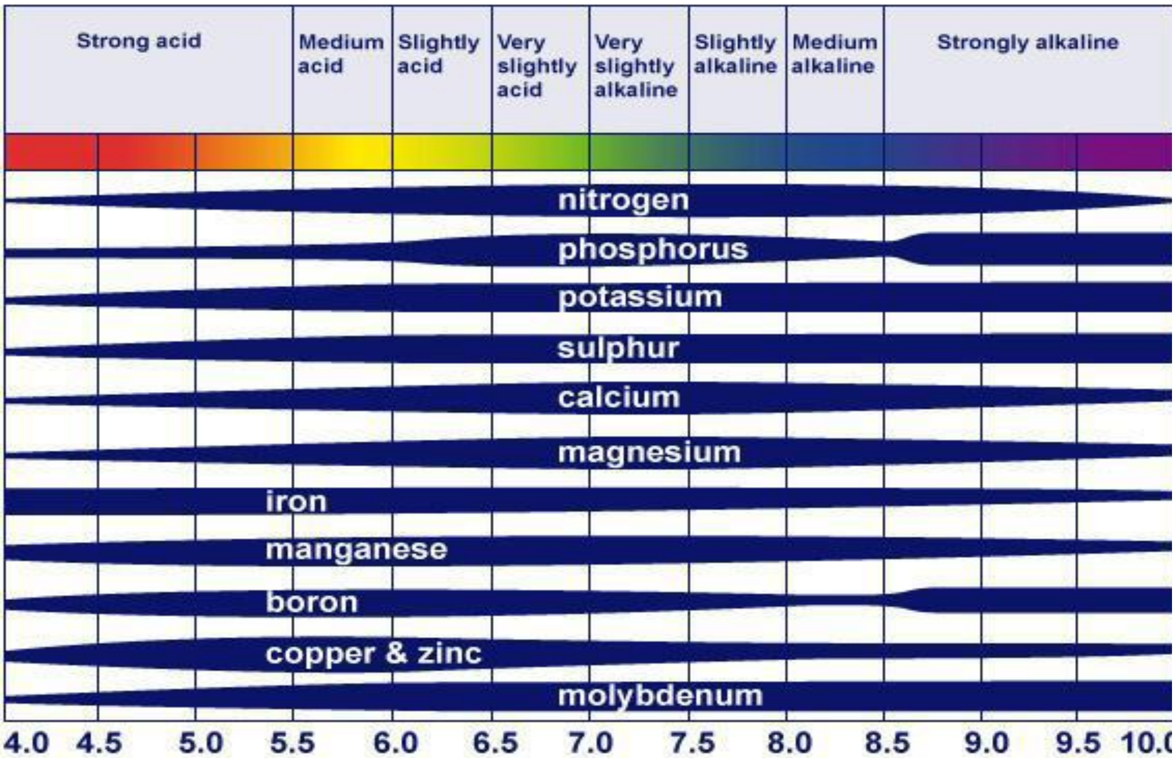


Figure 36: *Soil pH and the availability of nutrients for plant uptake. Source: (Jackson & Meetei, 2018)*

Among the most important causes of soil acidification on agricultural land is the application of urea (Goulding, 2016). This could be the reason for the soil pH decreasing from 5.7 in the control pots to 5.2 in the N&P-only pots following the application of N, in the form of urea fertiliser.

Lime at 4.0 t/ha produced a pH of 5.1 and was the most effective non-Si protocol. However, soil with a pH of less than 5.5 indicates the presence of exchangeable Al (Alam et al., 1999) and therefore the likelihood of a reduced crop yield. While lime at 4.0 t/ha was the most effective non-Si protocol, and among the most effective overall, it was not effective enough to increase soil pH for optimal crop yield. Compounds A and B produced a soil pH that was also outside the optimal range with a low of 5.0 and a high of 5.2.

In relation to soil pH, the most effective protocol was Compound-C, at both the low and high rate, which produced a soil pH of 6.3 and 6.5 respectively. A pH of 6.3 and 6.5 fits comfortably within the optimal range for nutrient availability and indicates the absence of exchangeable Al.

The soil pH results produced by Compound-C correlate to and were likely a partial cause of, the yield and economic outcomes of this study's tests wherein Compound-C consistently produced the best results.

Even at micromolar concentrations, Al can inhibit the root growth of some plants (Singh et al., 2017). In general, Al is toxic to plants at a concentration of 2.0 to 3.0 mg/kg (Påhlsson, 1990). The negative effects of Al on plants typically occur in acid soils with a pH of 5.5 or less (Rout et al., 2001). Of specific relevance to this study is the fact that Al can create disorders in the uptake of N, particularly nitrate-N, and P by corn plants (Krstic et al., 2012).

Compounds B and C demonstrated the ability to reduce exchangeable Al below the toxic level of 2.0 mg/kg and counteract the toxic effects of Al on crop yield. While Compound-B had a lower than ideal pH it still reduced the concentration of exchangeable Al below the toxic level of 2.0 mg/kg. It is likely that the absence of Al toxicity is at least a partial reason for Compound-B's yield and economic results.

Compound-C was highly effective and in addition to increasing pH to within the optimal range for nutrient availability, they also reduced exchangeable Al to undetectable levels which equates to a concentration of less than 0.2 mg/kg. The optimal pH and absence of exchangeable Al are likely to be at least a partial reason for the yield and economic results of Compound-C.

All three Si-rich compounds demonstrated a clear superiority to lime in regulating pH and counteracting exchangeable Al. However, the economic results from the trial demonstrated that only Compounds B and C can replace lime. The replacement of lime increases the economic viability of the leaching mitigation strategy. The economic results of this trial are presented in Table 28.

Table 28: *Economics of the trial plant yields grown with added Al*

Protocol	**Inputs Cost per ha**	**Fresh Weight Yield**	**Fresh Weight Yield Cost**	**Cost per Unit of Fresh Weight**	**% Increase in Units**
N & P Only	$648.00	40	$16.20	$0.41	0.0%
N, P + Lime 2.0 t/ha + Al 200 µmol	$720.40	21	$34.30	$1.63	-47.5%
N, P + Lime 4.0 t/ha + Al 200 µmol	$792.80	25	$31.71	$1.27	-37.5%
N,P + Compound-A 1.0 t/ha + Al 200 µmol	$828.00	33	$25.09	$0.76	-17.5%
N,P + Compound-A 2.0 t/ha + Al 200 µmol	$1,008.00	41	$24.59	$0.60	2.5%
N,P + Compound-B 1.0 t/ha + Al 200 µmol	$868.00	45	$19.29	$0.43	12.5%
N,P + Compound-B 2.0 t/ha + Al 200 µmol	$1,088.00	45	$24.18	$0.54	12.5%
N,P + Compound-C 1.0 t/ha + Al 200 µmol	$878.00	58	$15.14	$0.26	45.0%
N,P + Compound-C 2.0 t/ha + Al 200 µmol	$1,108.00	66	$16.79	$0.25	65.0%

The economics of Compound-A at both the low and high rates were superior to the lime protocols. However, the yield cost and cost per unit were not economically effective and ruled out Compound-A for use at regulating pH and counteracting exchangeable Al.

Compound-C at the low and high rate produced significantly better economics than any of the other protocols. The most telling data points are the cost per unit of fresh weight and the percentage increase in units which were both better than the corresponding plants grown with no added Al. Although yield improvements stimulated by Al have been observed in some plants, such as tea plants (Konishi, 1992), that have adapted to growing in an acidic environment, this is more of an exception than a rule (Rout et al., 2001). The increase in yield could have been caused by an Al-induced stress response of Si as opposed to direct Al stimulation.

The economic data identifies Compounds B and C as producing the best agricultural and economic results of all the pH and Al protocols and being an economically viable strategy to completely replace lime to regulate pH, and manage exchangeable Al. Therefore, the soil pH and Al components of the nutrient leaching mitigation strategy must be considered as aligned with the aspirations of Māori landowners.

5.7 Nutrient Concentration and Phosphorus Fixation

The efficient utilisation of N and P inputs is another means whereby agricultural efficiencies are increased and the cost of crop yield is decreased. Tests were conducted to determine the effect of Si-rich compounds on N utilisation, P fertiliser efficiency, and holding P in the soil while simultaneously keeping it in a plant-available form. The results from the tests were presented in the Results section of this study and showed that all the Si-rich protocols increased N and P fertiliser efficiency.

The plant uptake of N is generally less than 40.0% of the total amount of N in fertiliser that is applied to agricultural land (Malav Jugal & Ramani, 2017). The current literature indicates that Si has a role in increasing the efficiency of N fertilisers, particularly through improved N uptake by plants and by maintaining the level of N in the plant (Malav Jugal & Ramani, 2017; Neu et al., 2017). The environmental problems caused by the increased use of fertilisers and the associated reduction in fertiliser efficiency has meant that fertiliser efficiency has taken on increased relevance in agriculture (Weih et al., 2011).

Compound-C at 2.0 t/ha produced the best results of all the fertiliser protocols. N percentage in the soil ranged between a high of 0.27% and a low of 0.20%. While the degree of difference between Compound-C and the other protocols was not large there was a definite pattern related to the rate of fertiliser application. Lime at 4.0 t/ha had a lower percentage of total N than lime at 2.0 t/ha indicating that the higher rate of lime facilitated a greater uptake of N and therefore higher efficiency. Similarly, Compound-A at 2.0 t/ha had a lower percentage of total N than at 1.0 t/ha indicating that a higher rate of Compound-A facilitated a greater uptake of N. Compound-B at 2.0 t/ha had a lower percentage of total N than at 1.0 t/ha, and Compound-C at 2.0 t/ha also had a lower percentage of total N than at 1.0 t/ha all indicating that the higher rate of application was related to a higher uptake of N.

If overall efficiency was to be determined solely on the percentage of total N in the soil then N&P-only and lime at the low and high rate were the most efficient N uptake protocols. However, the crop yield results from the previous tests clearly show that the Si-rich compounds promoted greater plant biomass and the growth of biomass is the primary function of N in agricultural plants (Leghari et al., 2016). The significantly larger biomass yields of the plants grown with Si-rich compounds indicate a greater uptake of N than the non-Si protocols. If plant leaf analysis was undertaken the N efficiency of each protocol could have been determined by analysing the content of N in the plant tissue. Because leaf analysis was not undertaken the uptake and efficiency of N can only be inferred.

The current literature indicates that Si-rich compounds can improve the efficiency of P fertilisers by transferring plant-unavailable, or slightly soluble P into an available form (Liang et al., 2015a). The current literature also indicates that soil P fixation increases the volume of P fertiliser that needs to be applied to agricultural land and that lime can cause the fixation which in turn can lead to a P deficiency in plants and reduced yield rates (Kochian et al., 2004).

The results from the tests showed a substantial increase in Olsen P being held in the soil. Before the application of P fertiliser, the soil contained 17.0 mg/kg of Olsen P. As a direct result of applying P fertiliser Olsen P had increased to 42.0 mg/kg in the

N&P-only pots at the conclusion of the tests. While the application of lime increased the amount of Olsen P in the soil it did not meet the increase caused by the Si-rich compounds. With the advantage of being able to transfer a portion of the plant-unavailable P into an available form, the increase in Olsen P was substantially more than the lime protocols with the largest increase being found with Compound-C at 1.0 t/ha with Olsen P of 171.0 mg/kg.

The optimum Olsen P concentration for crop growth varies between soil and crop type but sits in the range of 20.0 to 55.0 mg/kg (Association, 2018; Roberts & Morton, 2016). An upper limit of 50.0 mg/kg has been recommended in New Zealand to protect the environment, particularly its water quality (Taylor et al., 2016). Every Si-rich protocol increased the concentration of Olsen P to well above the upper limit of the recommended range. This residual concentration of Olsen P can be utilised in subsequent years (Qihua et al., 2020). It is therefore possible to significantly reduce P fertiliser application in the future and take advantage of the residual Olsen P that is being held in the soil. Based on the upper limit of the recommended volume of Olsen P there is enough plant-available P being held in the soil to last for 2.0 – 3.0 years.

Olsen P is in a plant-available or soluble form. Total P is in a plant-unavailable or slightly soluble form. Insoluble P, which was not analysed for this study, is not plant-available and is insoluble. Every Si-rich protocol increased total P concentration to over 1,000.0 mg/kg and in the case of Compound-C to 1,869.0 and 1,912.0 mg/kg for 1.0 t/h and 2.0 t/ha respectively. The likely cause of such a large increase in total P is the transference of insoluble P into slightly soluble P. It is possible that with further applications of Si-rich compounds at least some of the huge total P reserve could be transferred into a plant-available form. It is also possible that with the further applications of Si-rich compounds the insoluble P could be transferred into a slightly soluble form. The slightly soluble form of P could then be transferred into a soluble form with further application of Si-rich compounds. If these residual forms of P are utilised it will represent a significant economic saving and an increase in P fertiliser efficiency.

The results of this trial demonstrate the effectiveness of the Si-rich compounds at increasing the efficiency of N and P fertilisers and mitigating P fixation. A detailed economic analysis was not conducted for this trial. However, the increased fertiliser efficiency and the creation of a large P soil bank strongly infer an economic benefit. The economic benefit of Si-rich compounds will continue over a period of years when the residual P in the soil bank is accessed thereby reducing the need to apply P fertilisers. Even if the effects of the Si-rich compounds do not provide an economic increase, because the effects happen simultaneously with the economic outcomes of all the previous tests at the very least this component of the strategy is economically neutral. Therefore, the fertiliser efficiency and P fixation components of the nutrient leaching mitigation strategy must be considered as aligned with the aspirations of Māori landowners.

5.8 Column Leaching Experiment

Residual P being held in the soil poses a large nutrient leaching risk and the risk of environmental harm is increased if the P is in a soluble plant-available form (McDowell, 2008). Therefore, while the large P bank created with the use of Si-rich can offer benefits it also brings into question the mitigation strategies environmental compatibility. Also, the efficiency of both N and P is in question if its removal from the soil was through leaching and not through plant uptake. A column leaching experiment was conducted to determine the effects of Si-rich compounds on the volume of N and P leaching and the data from the experiment were provided in the Results section of this thesis.

The concentration of N and P found in the leachate from the column experiments showed a significantly lower rate of leaching from the Si-rich compounds than from the N&P-only and lime protocols. The Si-rich compounds reduced ammonium N by up to 72.0% and nitrate-N by up to 85.0%. The Si-rich compounds were not as effective at reducing P leaching as the lime protocols. However, Compound-C at 2.0 t/ha was still able to reduce P leaching by 95.0%.

The concentration of N and P found in the soil at the conclusion of the column experiment showed that the Si-rich compounds held more ammonium N and nitrate-N in the soil than non-Si protocols by an average of 9.0 and 20.0% consecutively. Olsen P was in significantly higher concentrations in the soil of the Si-rich compound protocols than the non-Si protocols. The Olsen P results mirrored the results from the nutrient concentration and P fixation results wherein the Si-rich compounds held 2 to 3 times the amount of Olsen P in the soil than the lime protocols. The use of lime resulted in lower Olsen P concentrations than N&P-only, which suggests that the lime increased the rate of leaching or transferred the plant-available P into an unavailable form.

The small amount of N leaching during the column experiment strongly infers that the low concentration of N in the previous nutrient concentration trial was due, at least in part, to plant uptake efficiency. However, there was no way to determine the rate of N volatilisation from the water or soil analysis therefore the uptake efficiency is inferred. The small amount of P leaching during the column experiment strongly infers that the Si-rich materials could hold high concentrations of residual plant-available P in the soil without it leaching. This result can relieve concerns regarding the potential for the large volume of residual P, created by the application of Si-rich compounds as demonstrated in the previous trial, leaching into natural waters.

The results from the column leaching experiment demonstrate the ability of the Si-rich compounds to not only significantly reduce nutrient leaching but also to reduce nutrient leaching quickly and efficiently. The results from this column experiment concur with previous column and field leaching experiments in terms of effectiveness and timeframe to achieve results (Matichenkov et al., 2020; Matichenkov et al., 2005). Therefore, the nutrient leaching component of the nutrient leaching mitigation tool must be considered as aligned with the aspirations of Māori landowners.

5.9 Leaching Mitigation Reference Tool

The data collected from the pot trials and column experiments provided multiple data points that were collated in such a way as to provide concise information from which decisions can be made regarding the mitigation of nutrient leaching. Specifically, the data was used to create a reference tool that is designed to provide Māori landowners with the data they need to make the most appropriate choices concerning their farming, environmental and economic situation and needs. The tool can also provide Māori with a level of independence and allow at least a measure of self-determination as kaitiaki of their land and their farming operations. The leaching mitigation reference tool is provided in full as Table 29.

Table 29: *Leaching mitigation reference tool.*

ONE TONNE PER/HA									
Active Silicon (mg/kg)	**Cost**	**N, P, Si Input Cost**	**Yield at 20% Less N & P**	**Nitrogen Leaching**	**Phosphorus Leaching**	**pH**	**Aluminium**	**Fertiliser Efficiency**	**Phosphorus Retention**
1,200 - 1,300	$180.00 per/ha	$698 per/ha	+ 5 to 15%	- 20 to 50%	- 20 to 60%	N/A	N/A	A	AA
2,000 - 2,200	$220.00 per/ha	$738 per/ha	+ 10 to 20%	- 30 to 60%	- 25 to 65%	B	AA	A	AAA
4,000 +	$230.00 per/ha	$748 per/ha	+ 20 to 50%	- 35 to 75%	- 30 to 70%	AA	AAA	AAA	AAA
Active Silicon (mg/kg)	**Cost**	**N, P, Si Input Cost**	**Yield at 40% Less N & P**	**Nitrogen Leaching**	**Phosphorus Leaching**	**pH**	**Aluminium**	**Fertiliser Efficiency**	**Phosphorus Retention**
1,200 - 1,300	$180.00 per/ha	$568 per/ha	+ 2 - 5%	- 20 to 50%	- 20 to 60%	B	B	A	AA
2,000 - 2,200	$220.00 per/ha	$608 per/ha	+ 5 - 15%	- 30 to 60%	- 25 to 65%	B	AA	AA	AAA
4,000 +	$230.00 per/ha	$618 per/ha	+ 10 - 20%	- 35 to 75%	- 30 to 70%	AA	AAA	AAA	AAA
TWO TONNES PER HECTARE									
Active Silicon (mg/kg)	**Cost**	**N, P, Si Input Cost**	**Yield at 20% Less N & P**	**Nitrogen Leaching**	**Phosphorus Leaching**	**pH**	**Aluminium**	**Fertiliser Efficiency**	**Phosphorus Retention**
1,200 - 1,300	$360.00 per/ha	$878 per/ha	+ 10 to 20%	- 25 to 65%	- 20 to 60%	N/A	N/A	A	AA
2,000 - 2,200	$440.00 per/ha	$958 per/ha	+ 15 to 40%	- 35 to 70%	- 25 to 65%	B	AA	A	AAA
4,000 +	$460.00 per/ha	978 per/ha	+ 25 to 60%	- 40 to 75%	- 30 to 70%	AA	AAA	AAA	AAA
Active Silicon (mg/kg)	**Cost**	**N, P, Si Input Cost**	**Yield at 40% Less N & P**	**Nitrogen Leaching**	**Phosphorus Leaching**	**pH**	**Aluminium**	**Fertiliser Efficiency**	**Phosphorus Retention**
1,200 - 1,300	$360.00 per/ha	$748 per/ha	+ 5 - 15%	- 25 to 65%	- 20 to 60%	N/A	N/A	A	AA
2,000 - 2,200	$440.00 per/ha	$828 per/ha	+ 10 - 20%	- 35 to 70%	- 25 to 65%	B	AA	AA	AAA
4,000 +	$460.00 per/ha	$848 per/ha	+ 10 - 25%	- 40 to 75%	- 30 to 70%	AA	AAA	AAA	AAA

The first column of the reference tool details the concentration of active-Si and its application rate to produce specific agricultural and environmental outcomes. Each agricultural and environmental outcome is different for each concentration and application rate of active-Si. The second column details the cost of each concentration and application rate of active-Si, and therefore the cost to obtain the specific agricultural and environmental outcomes. The third column provides the combined cost of active-Si plus urea and superphosphate at a 20% and 40% reduced rate of application.

The fourth column details the first specified agricultural outcome which is the expected range of increase in crop yield. Māori landowners will be able to use these features of the reference tool to determine which option best fits their crop production needs relative to their economic position. The fifth and sixth columns detail the first and second specified environmental outcomes by providing an expected range for the reduction of N and P leaching. In the same way that Māori landowners can use the reference tool to determine their best crop productivity option, the best nutrient leaching option can also be selected relative to economics and crop productivity.

Columns seven, eight, nine, and ten detail the remaining agricultural and environmental outcomes. Unlike the previous columns which provided a range of expected outcomes, these columns provide a rating on the effectiveness of each fertiliser protocol in regulating soil pH, counteracting the effects of Al, fertiliser efficiency, and the retention of plant-available P in the soil. The ratings are based on the outcomes of the pot trials and column experiments. Based on the physical and chemical properties of their soil, Māori landowners can select the input option that can best meet the needs of their soil relative to economic, crop productivity, and nutrient leaching requirements.

The crop yield and nutrient leaching rates used in the reference tool are lower than the pot trial and column leaching results. The rates are also expressed as a range and not as a single number. Pot trials and column experiments are standard and commonly used methods to examine and assess agricultural practices and outcomes. In comparison to field trials, pot trials and column experiments are more repeatable, reproducible, cheaper, and easier to manage. As a result the number of pot experiments, as determined by the number of published studies utilising pot trials, has increased by over 300.0% between 1995 and 2015 (Hohmann et al., 2016). However, the transference of results from pot trials to natural field conditions, particularly in trials that study responses to biotic and abiotic stress, do not always match (Hohmann et al., 2016; Poorter et al., 2016). Column leaching experiments can also produce different results from chemical leaching analysis methods and have been found to over predict the volume of leached chemicals (Grathwohl & Susset, 2009; Schuwirth & Hofmann, 2006). The coefficient between outdoor pot trials and column leaching with field performance can range from 0.30 to 0.70 (Löv et al., 2019; Ogunkunle & Beckett, 1988). Therefore, the values provided in the reference tool are reduced to reflect this coefficient variance.

The pot trials determined that the Si-rich compounds, particularly Compounds B and C could replace lime for the function of pH regulation and to reduce the effects of Al. The Si-rich compounds produced better results to lime for every tested parameter except for reducing P leaching. The most effective lime protocol reduced P leaching by 2.1 ppm more than the most effective Si-rich compound. However, the lower economic results and the lower crop yield, N leaching, nutrient retention, pH regulation, and Al control does not warrant the inclusion of lime based on a 2.1 ppm improvement in P leaching. Therefore, the reference tool does not include lime in any option.

The cost of transportation and spreading of the fertiliser inputs is not included in the reference tool. The cost between farms has too many variables to determine with a level of accuracy, some farmers have their own spreading machine, some have their own freight trucks, some farms are located hours away from freight depots while others are within a few kilometres, and the size of the farm and the volume of fertiliser required can also affect transportation and spreading costs. However, with the replacement of lime, which is typically applied at higher rates than the 1.0 to 2.0 t/ha required of the Si-rich compounds and a reduction in the volume of N and P fertiliser the transportation and spreading cost should be less.

5.10 Limitations of the research

The major limitation of the pot trials and column leaching experiments was that they were conducted on one type of soil. There is a huge range of variations in agricultural soil, not just from farm to farm but from paddock to paddock on the same farm. The pot trials and column leaching experiments of this study measured multiple agricultural and environmental parameters using multiple testing protocols. The data collected from the pot trials and column experiments provided dozens of data points detailing crop yield, fertiliser use, nutrient leaching, nutrient soil retention, soil pH, and Al. However, despite a substantial amount of data being collected from the research the entirety of the data was related to a single soil type that had physical and chemical properties unique to the specific soil used in the trials and experiments.

Not conducting leaf analysis on the plants grown for the Al, fertiliser efficiency, and nutrient concentration trials limited the information gained about these testing parameters. Leaf analysis would have provided an understanding of the concentration of Al in the plant and therefore the ability of the Si-rich compounds to reduce plant uptake of the element. Even though the leaf analysis would not have altered the determination of the Si-rich compound's superiority over lime at counteracting the effects of Al, a clearer understanding of the processes that affect the economic outcomes could have been possible. Understanding the concentration of N and P in the plant tissue would have provided a greater understanding of the regulation of N and P uptake by plants and the increased fertiliser efficiency provided by the Si-rich compounds.

The limitations of the research can be addressed with a broader range of testing parameters and methods. The collection, creation and use of different soils types with different physical and chemical properties to increase the accuracy and applicability of the trial and experiment results, and therefore the reference tool, is only a matter of increasing the trial size and the availability of money to pay for the larger amount of trials and analytical testing. Leaf analysis can also be added to the testing parameters and methods.

5.11 Further Research

Pot trials are considered to be an important early step in determining traits and responses of agricultural plants. However, verifying the results from the pot trials under field conditions can provide a broader understanding of the tested parameters (Hohmann et al., 2016). Therefore, further research should include the replication and verification of the trials under field conditions.

Due to the limitations of this study's research, more soil and crop types should be tested to broaden the direct applicability of the results under farming conditions. The main reason for the study concentrating on N and P is that these two nutrients cause the most damage when leached into natural waters (Smith et al., 2016). However, concentration on these two nutrients is not reflective of a true farming system or the agricultural outcomes facilitated by Si-rich compounds. Therefore, more agricultural parameters should be included in further research, including a range of N and P fertiliser types, a range of K fertiliser types, and micronutrients.

The results from the pot trials and column experiments showed that a higher concentration of active-Si is more important than higher application rates of Si-rich compounds that have lower concentrations of active-Si. Compound-B at 1.0 t/ha consistently out-performed Compound-A at 2.0 t/ha, and 1.0 t/ha of Compound-C typically outperformed 2.0 t/ha of Compound-B even though the total volume of active-Si would be greater in the 2.0 t/ha application. The economics of using Si-rich compounds makes it possible to use more efficient products with higher concentrations of active-Si than used in this study. This could be achieved by either purchasing higher quality products or activating natural silicate minerals with a larger volume of concentrated monosilicic acid. Compound-B was activated with a 28.0% liquid Si product at a rate of 20:1. This volume of concentrated monosilicic acid is considered a low rate with the standard rate being 10:1. Further research should include agricultural, environmental, and economic outcomes of using Si-rich compounds with higher concentrations of active-Si. The boundaries of diminishing returns for agricultural, environmental, and economic outcomes based on applying increasing concentrations of active-Si should also be researched.

Further research should include strategies to reduce the amount of heavy metals and other contaminants in agricultural inputs and the reduction of the leaching of these substances into natural waters, both of which could be facilitated by Si-rich compounds. The ability of Si-rich compounds to help protect a plant from biotic stresses such as insects, fungi, and diseases could facilitate a reduction in the use of agricultural inputs such as insecticide and fungicide. The reduced use of these inputs could have a positive economic and environmental benefit and could therefore be included in further research.

CHAPTER SIX

Conclusion

6. Conclusion

The results of this study suggest that nutrient leaching from farmland into natural waters can be reduced with a mitigation strategy that utilises Si-rich compounds. Further, the results of this study have shown that the mitigation strategy is compatible with the principles and values of kaitiakitanga and is also economically viable. Therefore, Māori landowner aspirations, as identified by Dewes (2011), could potentially be achieved using the Si-rich leaching mitigation strategy.

The analysis performed on the Si-rich compounds used in this study determined that Compounds A, B, and C contained 1,220.0 – 1,310.0, 2,100.0 – 2,180.0, and 4,171.0 mg/kg of active Si respectively. The different concentrations of active Si generally determined the results of the pot and column tests. The higher the concentration of active Si typically correlated to the best agricultural, environmental and economic outcomes.

The data obtained from the pot trials showed that the Si-rich compounds produced a larger crop yield at a higher net profit margin than every N, P and lime protocol it was compared with. The data obtained from the column leaching experiments showed that the Si-rich compounds are a prompt and highly effective means of reducing N and P and overall were more effective than the non-Si protocols.

A key aspect in determining the attainment of this study's objective is the economic outcomes produced by the leaching strategy. Of primary economic importance was the leaching strategy's ability to increase farming profitability to the point that the strategy not only paid for itself but generated a healthy surplus. Pivotal to the economic success of the leaching strategy was its ability to increase crop yield, reduce the amount of N and P fertiliser required, and totally replace lime for the regulation of pH and to counteract the effects of aluminium toxicity. The Si-rich compounds also increased fertiliser efficiency, reduced P fixation in the soil, and held a large soil bank of P in a plant-available form that could be accessed in the coming years. All of these outcomes would contribute to the economic effectiveness of the leaching strategy.

The results from the pot trials and column leaching experiments enabled the creation of a reference tool that Māori landowners can use as part of their decision-making process to achieve the agricultural, environmental and financial goals they have for their land and to fulfil their responsibilities as kaitiaki.

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