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CADMIUM MANAGEMENT IN NEW ZEALAND'S HORTICULTURAL SOILS

A thesis presented in partial fulfilment of the requirements for the degree of
Master of Environmental Management

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Abstract

Cadmium (Cd) is a heavy metal trace element which presents risks for the horticultural industry in New Zealand (NZ). This element is added to soils through phosphate fertiliser application, and once there may be available for plant uptake and food chain transfer. When food products exceed international standards for Cd concentrations, these products may be excluded from international markets upon which NZ relies to maintain its economy. This presents a reputational risk for NZ's horticultural exports. Soil pH and organic matter (OM) content are the two key drivers influencing Cd's bioavailability, and field trials are currently being undertaken in four horticultural sites throughout NZ – Pukekawa, Manawatu, and two adjacent sites at Lincoln – to test the efficacy of the use of lime and compost amendments to influence these soil variables and thus reduce Cd plant uptake from soils. Potatoes are grown at all sites while Lincoln also includes wheat. This research aimed to characterise these soils, including total and plant-exchangeable Cd concentrations, pH, OM content, cation exchange capacity, total and plant-exchangeable Zn concentrations, aluminium and iron oxide content, total phosphorus and total nitrogen content. Findings indicated that total Cd concentrations varied among sites, with the highest (0.52 mg kg^{-1}) at Pukekawa, followed by Manawatu (0.26 mg kg^{-1}) and Lincoln Wheat and Potato sites (both 0.13 mg kg^{-1}). Exchangeable Cd concentrations were low at all sites ($0.01\text{-}0.02 \text{ mg kg}^{-1}$) indicating little risk of plant uptake from these soils.

The mitigation strategy tested in this work focuses on pH as a key soil variable that can be readily changed to restrict Cd uptake. However, the effectiveness of amendment rates to effect target pH values is dependent on soil chemistry and rates will vary across sites. Incubation experiments were conducted to determine amendment rates for lime and sulphur, and to compare the pH of amended soil in a laboratory situation with the in-field situation. Incubation and field situations were found to be similar, with no significant differences between pH values after a period of 274 days in the incubator and 169 days in the field. The accuracy of the calculated amendment rates at achieving target pH values was assessed with extended incubation experiments. The results here varied between soils, with the sulphur application rate proving more accurate in the Pukekawa soil, however too high for the Manawatu and Lincoln potato soils. The calculated liming application rate similarly resulted in a higher-than-target pH, however after a period of 231-274 days the pH reduced and approached the target value.

A cost-benefit analysis was undertaken to determine the economic viability of the proposed mitigation strategy at each potato site. Results proved the strategy to be a viable option, which would remain viable in the face of varying uncertainty and reductions in potato yields. Practical considerations including timing and weather conditions, and compost availability were considered. Implementation of this strategy within NZ's current framework of the Tiered

Fertiliser Management System, which focuses on total rather than exchangeable Cd concentrations, may present difficulties, and thus there is a clear need for risk-based, soil and crop specific guidelines for Cd management within a NZ context.

Considering the apparent difficulties in designing pH amendments strategies, a model to convert pH buffer curve-generated lime application rates which can be derived in as little as 24 hours, to field applicable application rates which target a specific soil pH was developed for the Pukekawa soil. A similar model was not achieved for the Lincoln Wheat soil, and thus the development of such a model is not possible for all soil types. Where possible, the development of this model would be an innovative and useful tool for farmers with which to accurately and quickly determine required lime application rates to achieve a targeted soil pH. This would be of great benefit in the implementation of a Cd mitigation strategy using lime amendments, and would allow greater control over, and management of, soil pH in a horticultural context.

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1 Introduction

New Zealand is a country which thrives on horticultural productivity, as the national economy is reliant on horticultural exports. The success and sustainability of this industry is underpinned by the state of horticultural soils. Cadmium (Cd) is a soil contaminant which poses risks to this industry, as its existence in soils (due primarily to anthropogenic actions including phosphate fertiliser application) and its bioaccumulative and toxic nature mean that it can be readily transferred from soils to vegetable produce, thus entering human food chains (Loganathan et al., 2012). When this occurs food stuffs may exceed international food safety standards for Cd residue and thus face market rejection. This presents a reputational risk to NZ's horticultural industry (Cavanagh, 2015). Cadmium's bioavailability within soils is dependent on both soil and plant factors, and as such soil and plant specific guidelines are required to adequately manage this environmental issue (Cavanagh et al., 2015). Such guidelines are currently under development in NZ, however have not yet been put into practice.

Current research in NZ is focusing on the soil and plant factors responsible for regulating Cd bioavailability, and soil pH and organic matter (OM) content have been identified as key drivers here (Cavanagh, 2015). Field trials are ongoing in three NZ locations (with four individual sites) to assess the efficacy of a new mitigation strategy using lime and compost amendments to manipulate soil pH and OM content, with the aim of decreasing Cd bioavailability and plant uptake. Potatoes and wheat are the crops under investigation here, as non-compliance with food standards for Cd levels has been observed within these crops in NZ (Cavanagh, 2015).

The use of lime to effect a pH change in soils is a common agricultural practice. However, the determination of application rates to produce a targeted pH value from a soil's native pH is a more difficult task. This involves the use of a pH buffer curve, which then must be translated to field specific data. The development of a specific framework by which laboratory and field data may be converted would be a useful and innovative step for pH management in NZ soils.

As well as considering the science behind this mitigation, an environmental management perspective gives insights into the practicality, viability, and regulatory framework surrounding the implementation of this strategy. This is useful when considering social and economic barriers or opportunities which may come into play during the implementation process. Economic viability is particularly important, as this is often the main barrier to adoption of well researched mitigation strategies.

2 Background

2.1 Cadmium – A Non-Essential Trace Element

Cadmium is a heavy metal trace element which occurs geogenically at low concentrations (average 0.1-0.2 mg kg⁻¹) within the Earth's crust (Kabata-Pendias & Mukherjee, 2007, p. 294; Loganathan, Vigneswaran, Kandasamy, & Naidu, 2012). It is commonly used in alloys, pigments, nickel-Cd batteries, and in industries including power generation, communication, and aerospace (Bešter, Lobnik, Eržen, Kastelec, & Zupan, 2013). Cadmium is devoid of biological function, and is toxic to animals, plants, humans and soil microorganisms at high concentrations (Loganathan et al., 2012). As Cd is bioaccumulative, it is able to enter human and animal food chains through uptake from soil into plants, which can result in risks to physical health of both humans and animals (Bešter et al., 2013; Golia, Dimirkou, & Mitsios, 2008). When ingested, Cd primarily accumulates in the liver and kidneys of animals and humans, with a biological half-life of up to 19 and 38 years respectively in these organs (Agency for Toxic Substances and Disease Registry, 2008; Bolan, Adriano, Mani, & Duraisamy, 2003). As well as being nephrotoxic, Cd is considered a human carcinogen, and has been implicated in respiratory and musculoskeletal issues (World Health Organisation, 2010).

The majority of Cd sources to soils are anthropogenic, and include atmospheric deposition from industrial emissions, applications of biosolids and industrial waste, and applications of phosphatic fertilisers to productive land areas (Loganathan et al., 2003; Loganathan et al., 2012). Cadmium also exists in soils due to the Cd content of soil parent material which ranges from <0.03–2.6 mgkg⁻¹ (Loganathan et al., 2003, p. 503). Average global soil concentrations are estimated to sit between 0.06-1.1 mgkg⁻¹ (Kabata-Pendias & Mukherjee, 2007, p. 295).

Cadmium exists as a geogenic impurity within phosphate rock, with geographically variant concentrations (Loganathan et al., 2003). As phosphate rock is used to manufacture phosphatic fertilisers, Cd remains in fertiliser due to the lack of an economically viable method of removing Cd from the raw product (Loganathan et al., 2003; Sneath, 2015). Common agricultural fertilisers including single superphosphate (SSP), triple superphosphate (TSP), diammonium phosphate (DAP), and partially acidulated phosphate rock subsequently contain Cd at varying concentrations, which accumulates in soil with the repeated application of these fertilisers (Loganathan et al., 2003). As such, high soil Cd concentrations are likely to be found in areas with long histories of agricultural land-use. Cadmium has been shown to accumulate in the topsoil (0-7.5 cm depth), and does not readily leach (Gray, McLaren, & Roberts, 2003; Taylor, Gibb, Willoughby, Hewitt, & Arnold, 2007). This lack of leaching is thought to be due to soil sorption capacity, leachate pH and total drainage volume (Gray et al., 2003). Thus Cd poses little

significant threat to groundwater quality, however due to its long residence times in soil – between 200-700 years dependent on fertiliser type and land-use – it creates legacy issues for many productive regions (Loganathan et al., 2003). Furthermore, grazing animals are expected to return 99% of ingested Cd to soil through excreta, and in such cases this extends Cd's residence time in soils to the range of thousands of years (Loganathan et al., 2003). Thus Cd accumulation in soils is a longstanding issue.

2.2 Cadmium's Harmful Effects on Plants and Microorganisms

As well as posing risks to human and animal health, Cd also has harmful effects on soil biota and plants at elevated concentrations. Plants uptake Cd from soil pore water into leaves and root systems, in the forms of Cd^{2+} , organic chelates, and aqueous ions (Ciecko, Wyszowski, Krajewski, & Zabielska, 2001). Bešter et al. (2013) report that when levels of heavy metals in soils exceed safe concentrations, both the quality and the yield of horticultural crops can be decreased. Safe concentrations vary dependent on the type of crop, however phytotoxicity – and thus yield and quality declines – generally occurs at between 5-10 $mg\ kg^{-1}$ for crops, and between 10-30 $mg\ kg^{-1}$ for more tolerant species (Kabata-Pendias & Pendias, 1992).

In a study by Piotrowska, Dudka, and Wiacek (1992) Cd's inhibitory effect on plant growth was demonstrated as the yield of maize crops was negatively affected with increasing Cd soil concentrations. The most detrimental effects in this study were observed with soil concentrations of $>5\ mg\ kg^{-1}$. Ciecko et al. (2001, p. 39) further demonstrate the effect of Cd on crop yield, showing that spring triticale experiences decreases in yield of 35%, 53%, and 76% in grain, straw and root yields respectively when soil contains high (7.5–22.5 $mg\ kg^{-1}$) concentrations of Cd. In a study investigating the effect of lime amendments on the phytoavailability of Cd for mustard (*Brassica juncea* L.) plants, Bolan, Adriano, Mani, et al. (2003) found that the dry matter (DM) yield decreased as Cd concentrations in soils and plant tissues increased, again demonstrating Cd's phytotoxicity. This effect intensifies as soil pH declines, however any level of Cd addition to soils causes plant concentrations of Cd to increase thus inhibiting plant growth.

As well as affecting yield, excessive Cd concentrations in soil can result in disruptions to plants' metabolic processes (Ciecko et al., 2001). Wozny, Stroinski, and Gwozdz (1990) indicate that the primary effect of Cd is to negatively impact plants' biosynthesis of organic compounds and proteins. Ciecko et al. (2001) reported that when Cd contaminated (spiked) soil was used to grow spring triticale, changes occurred to the chemical composition of straw and grain. As the Cd content of grain increased, total nitrogen (N) decreased in a relative fashion. This effect was augmented when no lime or organic amendments were added to the soil. The magnesium (Mg)

content of the grain and straw was also shown to decline when spring triticale was grown in Cd contaminated soil. Furthermore, calcium (Ca) and sodium (Na) contents of grain, and the potassium (K) content in straw tended to increase relative to the concentrations of Cd in soils. Overall, Cieccko et al. found that when grown in Cd contaminated soil, the concentration of this metal in grain, triticale roots and oilseed rape increased by 26, 10 and two times respectively. Thus, Cd interferes not only with plant yield, but with plants' chemical composition and biogenic processes.

Legume based pasture systems rely on soil rhizobia for N-fixation to maintain pasture productivity (Zahran, 1999). Furthermore, in clover pasture systems, the symbiosis between rhizobia and clover plays an important role in N-fixation and thus is a critical factor concerning pasture growth (Zahran, 1999). Cadmium has been shown to have a negative impact on rhizobia growth in NZ soils, in particular on the current commercial rhizobia strain, *Rhizobium leguminosarum* TA1 (Cavanagh et al., 2015). As pasture growth underpins the majority of NZ's agricultural industries, Cd contamination of agricultural soils poses risks to the sustainability of these industries. It has also been suggested that high soil Cd concentrations may cause phytotoxicity in clover, as well as affecting the symbiosis between rhizobia and clover, and thus have further negative impacts on N-fixation in pastures (Cavanagh et al., 2015). Further work is currently under completion to assess this, and to determine safe Cd concentrations for rhizobia growth in a NZ context (Cavanagh et al., 2015).

2.3 Soil Characteristics Influencing Cadmium Bioavailability

2.3.1 Total and Exchangeable Cadmium Content

When Cd accumulates in soils, only a fraction of the total of this heavy metal is available for plant uptake while the majority (>98%) remains associated with soil colloids (Al Mamun et al., 2016a). As such, while high concentrations of Cd in soils relative to background levels indicate contamination, this does not in itself constitute pollution or environmental risk (Chapman, 2007). Risk – and therefore pollution – occurs when Cd in soils is phytoavailable, and thus exposure pathways are created for this contaminant to reach humans and animals resulting in negative outcomes. Thus it is phytoavailable Cd which poses the greatest amount of risk in agricultural soils.

This plant-available amount consists of the Cd found in soil solution, which exists as free metal ions (Gray & McLaren, 2006). This is most effectively measured as exchangeable Cd, using neutral or non-chelating extractants including 0.05 M Ca(NO₃)₂, 0.05 M CaCl₂, or 1 M NH₄OAc (pH 7) (Gray, McLaren, Roberts, & Condon, 1999c). Therefore, the bioavailable Cd concentration within a particular soil may be low, despite a high total Cd concentration. However,

many studies have found that one of the primary factors influencing Cd bioavailability and plant uptake is the total Cd content of soils. Regression models have been utilised by several authors, including Alloway, Jackson, and Morgan (1990); McBride (2002); and Zupan (2003) to determine total Cd content of soils as a primary influence on plant Cd concentrations. Bešter et al. (2013) expanded on this work, using regression models to determine the soil factors which most effectively predicted Cd concentrations in nine food crops, including potato, cabbage, red beet, chicory, tomato, carrot, onion, endive and zucchini. They found total soil Cd concentrations to be the most common and statistically significant factor for all vegetables except zucchini (for which no significant regression model could be developed), followed by organic matter (OM) content.

In a study addressing the solubility of heavy metals in soils which had been contaminated for long periods of time, McBride, Sauve, and Hendershot (1997) found that soluble Cd concentrations had a strong relationship with total soil Cd. This was also observed by Gray, McLaren, Roberts, and Condon (1999b) in a study conducted on 29 pastoral topsoils collected from throughout NZ. Gray and McLaren (2006) conducted a further study in which they aimed to generate empirical relationships between heavy metal soil concentrations and soil factors including total heavy metal content, total carbon (C) content, soil pH, and quantities of Fe and Al oxides within soils. The most significant factors influencing phytoavailable Cd were the total Cd concentration of soils, as well as pH and total C content. Furthermore, a study by Sauve, Hendershot, and Allen (2000) addressing the solid-solution partitioning of heavy metals in 64 contaminated soils of varying land-use found that 76% of the concentration of dissolved Cd in contaminated soils was due to both total soil Cd concentrations and soil pH. Thus there is agreement in the literature over the importance of total soil Cd to plant availability of Cd in soils.

2.3.2 Soil pH

The pH of soils is a factor which has been determined by many authors to influence plant uptake of Cd. In general, as soil pH increases, Cd plant uptake decreases (Kabata-Pendias & Mukherjee, 2007). One reason for this is that in high and neutral pH soil environments, calcium (Ca) ions (Ca^{2+}) compete directly with Cd ions (Cd^{2+}) for uptake sites on plant root surfaces, thus reducing the plant uptake of Cd from soils (Adriano, 1986). Furthermore, in acidic soil environments, there are a reduced number of negative sites available for Cd (in the form of positively charged Cd^{2+}) to adsorb to, and thus Cd mobility and plant uptake are increased with decreasing pH (Evans (1989). Within variable-charge soils, a pH increase will result in an increase in surface negative charge, which in turn results in increased adsorption of cations including Cd^{2+} (Naidu, Bolan, Kookana, & Tiller, 1994). Moreover, in soils with a high pH, CdOH^+ species may form, which are adsorbed more readily than Cd^{2+} (Bolan, Adriano, Mani, et al., 2003); Naidu et al.

(1994) however found that these species form when soil pH exceeds 8, which is unlikely within NZ's predominantly acidic soils. Additionally, Cd may undergo precipitation to form $\text{Cd}(\text{OH})_2$ when the soil pH exceeds 10, however, again, this is unlikely within NZ's soil environments (Naidu et al., 1994). Like zinc (Zn), Cd will become mobilised in soils exhibiting weak acidity, as compared to heavy metals such as nickel (Ni) and cobalt (Co) which require environments of higher acidity for dissolution to occur (Loganathan et al., 2003).

Along with total soil Cd, regression models have shown soil pH to be a statistically significant variable affecting plant uptake of Cd (Alloway et al., 1990; McBride, 2002; Zupan, 2003). In the regression model study by Bešter et al. (2013) mentioned above, soil pH was determined as a predictive factor concerning the Cd content of onions, along with total soil Cd concentration.

Gray, McLaren, Roberts, and Condon (1998) support this relationship between pH and Cd bioavailability, reporting that within a study addressing the effect of lime and pH on Cd sorption and desorption in six NZ topsoils, Cd sorption increased while desorption decreased when soil pH was increased from 4.9 to 6.2. This increased sorption occurred for both geogenically and anthropogenically sourced Cd. Gray et al. (1999c) built on this study, using 29 topsoils from pastoral sites throughout NZ to assess Cd sorption and desorption, and again determined soil pH to be the most significant soil factor affecting both geogenic and anthropogenic Cd in these soils. In a further glasshouse study by these same authors (Gray et al., 1999b), the influence of soil pH on Cd concentrations in lettuce, carrots, wheat, clover and ryegrass was assessed. Their results showed that when a pH increase from 5.5 to 7.0 occurred, Cd concentrations showed a significant decrease in carrots, lettuce, clover and ryegrass, with a smaller decrease observable in wheat plants. Gray et al. (1999b) did however maintain that there were variations in the magnitude of reduction between both soil types and plant species, and thus that Cd plant uptake is a complex process with co-dependent and interrelated variables.

Bolan, Adriano, Mani, et al. (2003) undertook a study whereby the pH of two soils was manipulated using $\text{Ca}(\text{OH})_2$ and KOH, and the adsorption of Cd was assessed. They found that as $\text{Ca}(\text{OH})_2$ and KOH caused an increase in pH, an observable increase in adsorption of Cd^{2+} occurred, with a resultant decrease in plant uptake. The authors assert that increases in negative charge induced by changes to soil pH are the primary explanation for increased Cd^{2+} adsorption and consequently the decrease in plant uptake. A study carried out in Central Greece by Golia et al. (2008) aimed to determine heavy metal (Zn, copper (Cu), chromium (Cr), Ni, lead (Pb) and Cd) concentrations in tomato, lettuce and potato crops grown in a range of soils (pH 5.5-7.5). Their results showed a negative correlation between the concentrations of all heavy metals and soil pH, and determined soil pH to be the primary factor controlling the solubility and plant uptake of heavy metals. A similar negative correlation was found in an earlier study by Gavi, Basta, and

Raun (1997), in which Cd concentrations in wheat grain were measured against soil pH ranging from 5.0-6.2. This study addressed the long term impact of soil pH and fertilisation on wheat grain (*Triticum aestivum* L.) Cd concentrations within continuous wheat systems in Mexico. Additionally, in a European study focussing on the relationship between agronomic practices and the Cd content of cereal grain and potato tubers, Mench (1998) observed a decrease in the Cd content of wheat grain DM (from 0.14-0.05 mg kg⁻¹) as pH was increased from 5.7-7.6. It is therefore observable that there exists a general agreeance within the literature concerning the relationship between soil pH and plant uptake of Cd, with plant uptake shown to increase as soil pH decreases.

2.3.3 Organic Matter Content

Soil OM consists primarily of detritus (active OM), humus (stable OM) and living microbial biomass and plant residues (Fenton, Albers, & Ketterings, 2008). The OM content is an important factor in soil productivity, as it provides benefits in many areas of soil health. These include soil biology, by providing nourishment for soil organisms and increasing microbial diversity within soils; soil physical parameters, by increasing soil's water infiltration, water-holding capacity, and soil aeration; and soil chemistry, by improving soils' buffering capacity and increasing cation exchange capacity (CEC), which allows soil to maintain concentrations of essential cation nutrients(Fenton et al., 2008). Organic matter may be added to soils in the form of amendments such as biochar, compost, animal waste, sawdust, and peat.

The OM content of soil is a further factor influencing Cd plant uptake (Johnston & Jones, 1992). This results as a high OM content means a soil will have a high CEC, which increases Cd adsorption within the soil (Roberts, 2014). Furthermore, OM has a high complexing ability and may form organometallic compounds with Cd in soil(He & Singh, 1993; Simmler et al., 2013).As these compounds are insoluble, they are unable to undergo plant uptake from soil solution and instead remain bound in the soil's solid phase (Simmler et al., 2013). Additionally, OM such as lignite (brown coal) is likely to contain heterocyclic sulphur (S) and organic S groups including R-S-R, R-SH, and R-SS-R, which Cd, as a chalcophilic element, is likely to bind strongly to (Calkins, 1994). Such binding may occur when Cd exists at relatively low but biologically significant concentrations, such as in contaminated agricultural soils (Simmler et al., 2013). Thus in general, as the OM content of a soil increases, plant uptake of Cd will decrease (Johnston & Jones, 1992). However, Roberts (2014) reports that soil OM may interact with soil pH, and thus have varying effects on Cd phytoavailability. At below pH 6, added OM has been shown to decrease Cd concentrations in soil solution, however at a soil pH of between 6-8, the opposite

effect is observed and Cd concentrations in soil solution increase (Roberts, 2014). This is demonstrative of the complexity and intersection of soil factors influencing Cd phytoavailability.

He and Singh (1993) demonstrated the effect of OM on phytoavailable Cd in a greenhouse experiment using three types of soil (a clay loam, sandy loam and sand). In this study, ryegrass (*Lolium multiflorum* L.) was grown with OM amended at six rates: 0, 20, 40, 80, 160 and 320 g OM kg air-dried soil⁻¹. Their results showed that Cd concentrations in ryegrass exhibited a strong negative correlation with CEC, and decreased as added OM increased. In terms of soil type, Cd concentrations in ryegrass decreased in the order of sand > sandy loam > clay loam. The relationship between CEC and plant uptake of Cd is consistent with the findings of a study assessing the relative influence of soil factors including CEC, OM content, Zn, and soil temperature on Cd uptake in oat shoots by Haghiri (1974). Both authors conclude that OM induced decreases in plant uptake of Cd are due to OM's influence on CEC. The more recent study by Golia et al. (2008) mentioned previously showed similar results concerning the Cd content of tomatoes, with plants grown in soils with higher OM contents exhibiting lower Cd concentrations.

Several studies conducted in a NZ pastoral context have shown that the majority of Cd (~84% of applied Cd according to Loganathan and Hedley (1997)) which has accumulated in soils as a result of past P fertiliser application, has accumulated within the topsoils of these pastures (Loganathan et al., 2003; Loganathan, Mackay, Lee, & Hedley, 1995; Roberts, Cameron, Bolan, Ellis, & Hunt, 1996). It has been suggested by all authors that the reason for such high recoverable Cd is the high OM content of the topsoils, resulting in adsorption and thus immobilisation of large amounts of the accumulated Cd within this area of the soil horizon. Furthermore, in Bešter et al.'s (2013) regression analysis, OM content of soil was determined to be a significant variable influencing Cd uptake by both onions and endive. It is asserted that this is due to OM's ability to bind with Cd, thus reducing the amount available for plant uptake.

In order to assess the effect of temperature and time on OM decomposition and the resultant changes to Cd sorption in two NZ soils, Cavanagh et al. (2015) conducted an incubation study whereby compost (as a source of OM) was added to soils, and these samples stored in an incubator at either 20°C or 30°C. The authors found that the C content of both soils at both temperatures was quickly increased with compost addition, however this began to decrease past week 9. Carbon content plateaued at week 13, and by week 49 showed only very small decreases. Slightly more C was retained in both soils at 20°C compared to 30°C, which indicates high OM decomposition at 30°C. Cadmium sorption within these soils follows the same trends as C content, initially increasing before decreasing after week nine. Over the course of the incubation, the unamended soil maintained greater concentrations of extractable Cd relative to the compost

amended soils. The results from this study are in agreement with the aforementioned literature, in that higher soil OM content generally results in decreased phytoavailability of soil Cd.

2.3.4 Cation Exchange Capacity

A soil's CEC is a measurement of its ability to hold onto exchangeable cations (those of most relevance to the soil's nutrient status being Ca^{2+} , Mg^{2+} , K^+ , Na^+ and H^+) (McLaren & Cameron, 1996). In effect, CEC measures the soil's quantitative negative charge per unit soil mass (McLaren & Cameron, 1996). As Cd^{2+} , like soil exchangeable cations, binds to soil colloid sites of negative charge (Cd does this through either specific or non-specific adsorption), the higher a soil's CEC, the more soil Cd it is likely to retain in the solid phase. As such, a higher CEC generally results in decreased plant uptake of Cd (Kabata-Pendias & Mukherjee, 2007; Roberts, 2014). As explained above, adding OM to soils results in an increase in CEC, as OM consists in part of humic substances which are predominantly negatively charged due to their ionisable carboxyl functional groups (Al Mamun et al., 2016a; McLaren & Cameron, 1996). As a result, humic substances within soil OM act to facilitate cation exchange and reduce the amount of Cd^{2+} available in soil solution (McLaren & Cameron, 1996). Furthermore, the consequent decreases in Cd plant uptake due to increases in soil pH – particularly in variable charge soils – have been attributed to increases in soil CEC or negative charge (Bolan, Adriano, Mani, et al., 2003; Loganathan et al., 2003).

2.3.5 Zinc

Zinc is a micronutrient with which Cd competes for plant uptake and translocation, and as such, alleviating Zn deficiencies or adding Zn to agricultural soils can result in reduced uptake of Cd by both foliar and root systems (Kabata-Pendias & Pendias, 1992; Loganathan et al., 2003; Roberts, 2014). Chaney and Hornick (1978) propose that when ratios of Cd:Zn within plant tissues are at or below 1%, Cd concentrations in plant matter will be below 5 mg kg^{-1} and thus will not reach phytotoxic levels (Kabata-Pendias & Pendias, 1992). Al Mamun et al. (2016a) report that when vegetables were grown in two soils with varying characteristics and Cd plant accumulation measured, the vegetables grown in soil with the lower Zn concentration (67 mg kg^{-1}) experienced increased plant uptake of Cd relative to vegetables grown in soil with a higher Zn concentration (173 mg kg^{-1}). Thus it can be advantageous to increase Zn levels within soils in order to reduce Cd accumulation by crops.

2.3.6 Aluminium & Iron Oxides

The presence of aluminium (Al) and iron (Fe) oxides in soils can impact plant uptake of Cd. In particular, increased Cd uptake is seen when the concentrations of these elements are low (de Meeûs, Eduljee, & Hutton, 2002; Loganathan et al., 2003). A decrease in Fe and Al (as well as manganese) oxides within soils causes a decrease in the soil's Cd sorption capacity, thus resulting in increased plant uptake (Loganathan et al., 2003). This occurs as these oxide compounds sorb Cd, thus reducing its mobility within soils (Backes, McLaren, Rate, & Swift, 1995). For example, relatively low soil concentrations of Al and Fe oxides in Gisborne soils are thought to be a primary reason for higher Cd uptake in spinach and silverbeet, compared with lower Cd uptake from soils in Pukekohe, which exhibit relatively higher Al and Fe oxide concentrations (Cavanagh et al., 2015). Thus, it is suggested that soils from Pukekohe and Waikato regions of NZ undergo relatively low plant uptake of Cd despite high total soil Cd concentrations, due to the presence of Al & Fe oxides in these soils (Cavanagh et al., 2015). However, the relative importance of this soil parameters for Cd plant uptake is thought to vary dependent on soil type (Cavanagh et al., 2015).

2.3.7 Total Phosphorus

Due to Cd's origins in phosphate rock, it has been determined in various studies that the prolonged use of P fertilisers on agricultural soils results in increased Cd concentrations in those soils relative to native background levels (Gray, McLaren, Roberts, & Condrón, 1999a; Loganathan et al., 1995; Rothbaum, Goguel, Johnston, & Mattingly, 1986; Taylor et al., 2007). As such, correlations can be found between P and Cd concentrations of such soils, primarily within the topsoil (0-7.5 cm depth) (Loganathan et al., 2003). As the P content of topsoil is indicative of the site's fertilisation history, P fertiliser application is a major factor influencing Cd accumulation in agricultural soils (Loganathan et al., 2003).

2.3.8 Total Nitrogen

Several studies have investigated the relationship between nitrogen (N) fertiliser application and Cd concentrations in wheat crops. In a field trial study conducted at three different sites in Canterbury, Gray, Moot, McLaren, and Reddecliffe (2002) assessed the impact of varying rates of N fertilisation on Cd concentrations in two durum wheat cultivars (*Triticum turgidum* L.). Nitrogen fertiliser was applied in the form of calcium ammonium nitrate (CAN) at two timepoints: tillering and flag leaf emergence. Their results showed that when CAN was applied at rates of 150-175 kg ha⁻¹ during tillering, and at rates of 25-100 kg ha⁻¹ during flag leaf emergence, the Cd

concentrations of both wheat cultivars at all three sites increased. The authors suggest several reasons for this: gradual soil acidification as a result of N fertiliser application; increased ionic strength of soil solution due to the application of fertiliser salts, resulting in displacement of non-specifically bound Cd; and enhanced root interception or mass flow as a result of increases in wheat yield due to N fertiliser application. The authors conclude that the latter explanation is the most likely in this case, as a correlation exists between increased plant yield and the Cd concentration of wheat grain. Thus they conclude that CAN applications can increase Cd concentrations in durum wheat, and attribute this to resultant increases in yield and subsequent increased water and solute translocation from soil solution to root zone to grain.

Wångstrand, Eriksson, and Öborn (2007) conducted a similar study in a Swedish context, addressing the effect of N fertiliser nitrate of lime applied at varying rates (100-235 kg N ha⁻¹ total) on the Cd concentrations of two winter wheat cultivars (*Triticum aestivum* L.). Their results showed, like those of Gray et al. (2002), that grain Cd concentrations were independent of soil Cd levels, and increased with increasing rates of N fertiliser application. As N fertiliser application increased by every 10 kg, Cd concentrations in grain showed an approximate increase of 0.001-0.003 mg kg⁻¹. Furthermore, the results showed a positive correlation between grain N and grain Cd. This correlation was supported by the results of a Swedish soil monitoring programme presented within this study, which showed that Cd grain concentrations positively correlated with N concentrations in oats, barley and winter wheat. The authors suggest that increases in grain Cd may be due to increases in soil Ca²⁺ as a result of fertilisation, which subsequently caused more Cd²⁺ to enter soil solution and undergo plant uptake as a result of ion exchange.

A further field study was conducted in Quebec, Canada, by Li, Ziadi, Belanger, Cai, and Xu (2011) to assess the effects of N applications at rates of 0, 40, 120, and 200 kg N ha⁻¹ (applied in two applications of CAN and ammonium nitrate at seeding and during the end of the crops' jointing stage) on a locally recommended cultivar of wheat (*Triticum aestivum* L., cultivar AC Barrie). In 11 out of 12 cases, Cd concentrations in wheat grain increased significantly as N application rates increased. Wheat grain concentrations here ranged from 34-99 µg Cd kg DM⁻¹, however did not exceed proposed tolerance levels for Cd in wheat grain of 235 µg Cd kg DM⁻¹. The authors concluded from this study that both soil Cd concentrations as well as the N nutrition status of wheat crops play a role in Cd accumulation in eastern Canadian wheat grain. Thus it is observable from the studies by Gray et al. (2002), Li et al. (2011), and Wångstrand et al. (2007) that site specific management including the use of N fertilisers can affect Cd plant uptake in agricultural systems.

Interestingly, a study by Cieccko et al. (2001) in which Cd uptake of spring triticale and oilseed rape was manipulated using lime and organic amendments, illustrated a reverse

relationship between plant Cd and N, with Cd contamination resulting in reductions in the total N content of spring triticale grain. However, in oilseed rape crops, Cd soil contamination resulted in increases in total N in aboveground portions of the crop. Thus, both crop and soil factors are seen to influence the interactions between Cd and N in agricultural systems.

2.4 Plant Factors Influencing Cadmium Bioavailability

2.4.1 Plant Species

Not all plants uptake Cd in the same quantities. As well as soil factors, various plant factors influence Cd plant uptake from agricultural soils. Plant species is one such factor, as numerous studies have shown differences in plant uptake of Cd which can be attributed to this (Bešter et al., 2013). Table 1 summarises the findings of several authors concerning rates of Cd accumulation by different types of vegetables. The majority of these authors agree that leafy vegetables tend to accumulate the most Cd, with root vegetables generally accumulating the median amount of Cd relative to other vegetables (Al Mamun et al., 2016a; Alexander, Alloway, & Dourado, 2006; Golia et al., 2008; He & Singh, 1993; Yang et al., 2010). Grains, legumes and fruit generally accumulate the least Cd relative to other crop types (Golia et al., 2008; He & Singh, 1993; Yang et al., 2010). The exception to these trends is Cavanagh et al. (2015), who report that Cd accumulation within food crops occurred in the reverse order, with wheat grain accumulating the most Cd and lettuce the least. Cavanagh et al. (2015) do however assert that this relative order of Cd accumulation is confounded by soil and site specific factors, as crops were grown in various locations of differing soil types throughout NZ.

It is generally accepted that lettuce is a high Cd accumulator, however Cavanagh et al. (2015) report that iceberg lettuce types appears to accumulate less Cd relative to cos, buttercrunch and loose-leaf lettuce types, and this may be a reason for the lower Cd concentrations observed in their study (Crews & Davies, 1985). As demonstrated by the differences in relative Cd accumulation between pasture crops in Waikato and Lincoln in Table 1, Cd uptake by specific plant species was not always consistent across all sites. However, chicory and plantain showed consistently higher Cd concentrations, indicating these species accumulate more Cd than other pasture species (Cavanagh et al., 2015; Stafford, Anderson, Hedley, & McDowell, 2016). This has potential to create issues around Cd concentrations in livestock, if the use of these pasture species leads to increased Cd food chain transfer as a result of high Cd uptake by these species.

Table 1. Differences in Cd accumulation between types of vegetables as reported by different authors

Author	Order of Cd accumulation
He and Singh (1993)	leafy vegetables > root vegetables > grain crops
Alexander et al. (2006)	lettuce > spinach > onion > carrot > pea > French bean
Golia et al. (2008)	leafy (lettuce) and root vegetables (potato) > fruit vegetables (tomato)
Yang et al. (2010)	leafy vegetables > solanaceous vegetables > kale vegetables > root vegetables > alliums > melon vegetables > legumes
Al Mamun et al. (2016a)	spinach > lettuce > onions
Stafford et al. (2016)	chicory > plantain > turnip > lucerne > sheep's burnet > strawberry clover > kale > perennial ryegrass > haresfoot trefoil > red clover > crimson clover > white clover
Cavanagh et al. (2015)	Food crops: wheat grain > potato > onion > lettuce
	Pasture crops (Waikato): chicory > plantain > ryegrass > lucerne > white clover
	Pasture crops (Lincoln): chicory > plantain > lucerne > ryegrass ~white clover
	Forage crops: sunflower > fodder beet > maize > kale

2.4.2 Plant Cultivar

As well as plant species, plant cultivar has also been shown to affect Cd uptake in crops. Cavanagh et al. (2015) conducted a survey to assess levels of Cd uptake in economically significant crop cultivars grown throughout NZ, including leafy green vegetables, potatoes, onions, wheat, forage crops and pasture species. High and low accumulating cultivars were identified for wheat and potatoes, with these cultivars showing consistent trends across all sites. Cultivars of onion and lettuce both showed inconsistency across sites, thus suggesting the importance of soil factors in determining Cd accumulation for these vegetables (Cavanagh et al., 2015). This site variation indicates an interaction between cultivars and soil properties in determining Cd uptake, thus demonstrating the site specificity of Cd plant uptake in NZ soils, and the complexity of managing this soil contamination issue (Cavanagh et al., 2015).

In the case of lettuce however, Cavanagh et al. did observe consistent trends of lower Cd concentrations in iceberg lettuce samples, which shows agreement with the conclusions drawn by Crews and Davies (1985) that butternut lettuces uptake more Cd from soil, followed by loose leaf and cos lettuce, with iceberg (or crisphead) lettuce generally accumulating the lowest concentrations of Cd. Cavanagh et al. (2015) further suggest that differences in Cd uptake between lettuce cultivars reported by Li, Dang, Cang, Zhou, and Zhou (2014); Zhang, Yuan, Kong, and Yang (2013) in studies aimed at understanding metal toxicity in lettuce cultivars, are in reality a result of lettuce type rather than cultivar.

Differences in Cd uptake between onion cultivars have been observed by Li, Zhou, Wi, and Ren (2012) in a screening study assessing the Cd uptake in Welsh onions. Li et al. (2012) identified two cultivars out of a total of 25, which exhibited relatively less Cd uptake. However, Alexander et al. (2006) assessed Cd uptake in six cultivars of onion, and concluded that no significant difference existed between cultivars. The variation in these results, along with those

of Cavanagh et al. (2015) which showed inconsistency in Cd uptake by onions across sites, suggests soil factors may be a more significant influence on Cd accumulation than onion cultivar or species.

Wheat was the only crop in Cavanagh et al.'s (2015) study for which both high and low accumulating cultivars could be identified. The authors here noted a 2.4-fold difference between Cd concentrations in wheat grain of individual wheat cultivars. They also noted that Cd concentrations were consistently higher in wheat bran than in wheat flour. This noticeable difference in Cd accumulation between wheat cultivars has been reported in previous literature (Gray, McLaren, & Roberts, 2001; Gray et al., 2002; Kubo et al., 2008; Roberts, Longhurst, & Brown, 1995). In one such study, Gray et al. (2001) measured variations in Cd concentrations of wheat (*Triticum aestivum* L.) grain grown at eight sites throughout NZ, and found a 4-fold range in the capabilities of different wheat cultivars to uptake Cd. These differences in Cd uptake between wheat cultivars are attributed to genotypic variation governing the translocation of Cd from plant roots to shoots (Cavanagh et al., 2015; Harris & Taylor, 2013).

Where identified, these differences in Cd accumulation between plant cultivars may help in reducing food chain transfer of Cd through crops. Low-accumulating cultivars represent an opportunity to grow food crops on soils which contain moderate Cd concentrations without this Cd accumulating in crops at toxic concentrations and thus breaching food standards, and may also be used to breed low Cd cultivars of specific crops for wider use (provided there is no yield reduction as a result) (Cavanagh et al., 2015).

2.4.3 Plant Tissue

Type of plant tissue is a further factor effecting Cd accumulation in plants. The general order of accumulation in plant tissues is:

leaves and stem > roots, fruit, grain > tubers

(Cavanagh et al., 2015; Golia et al., 2008; Hu et al., 2013; Loganathan et al., 2003). This order of accumulation in plant tissue is consistent with the orders of accumulation in plant type presented in Table 1, with leaves and leafy vegetables accumulating the most Cd respectively. This follows that if the leaves of a plant accumulate the most Cd, crops which consist primarily of leafy parts will accumulate more than other types.

More specific differences have been observed in individual species by several authors. In Cieccko et al.'s (2001) aforementioned study, higher concentrations of Cd accumulated in the grain and roots of spring triticale, relative to the straw. Cieccko et al. noticed 26-fold and 10-fold increases in grain and root Cd concentrations of spring triticale respectively as a result of soil Cd

pollution, with significantly less pronounced differences to the Cd content of straw. Cavanagh et al. (2015) reported consistently higher Cd concentrations in the leaves of all crops relative to other plant portions. Maize, for example, showed no detectable Cd within the cob, however leaf concentrations averaged 0.022 mg kg⁻¹ fresh weight (FW). Potato peel was also shown by Cavanagh et al. (2015) to contain higher Cd concentrations relative to potato tubers, with overall Cd concentrations in potato following the order of:

stem > leaf > skin > tuber

These results show that trends in Cd accumulation between potato plant tissues generally follow and support the order detailed above, with stem and leaf concentrations being higher than tuber Cd concentrations (Cavanagh et al., 2015).

2.4.4 Leaf Age

As Cd accumulates in plant tissues over time, it follows that older tissues will have the opportunity to accumulate more Cd than younger tissues (Bešter et al., 2013; Loganathan et al., 2003). Thus leaf age is a key plant factor concerning Cd accumulation by plants. As Cd is bioaccumulative, it is unable to be easily expelled from plant and animal tissues once it has been absorbed. Therefore, younger crops are likely to have accumulated less Cd relative to older crops and hence tend to exhibit relatively lower Cd concentrations (Cadmium Working Group, 2008). However, if high concentrations of exchangeable Cd are present in soil, harvesting young leaves may still present a risk. Looking at variables such as growing time may be advantageous when seeking low Cd accumulating plant species and deciding between plant cultivars.

2.5 Cadmium Accumulation in a New Zealand Context

2.5.1 Background

The issue of Cd accumulation in agricultural soils became recognised in NZ during the 1990s, when it was discovered that approximately 20% of kidneys and livers from NZ sheep and cattle exceeded maximum permissible levels for Cd in offal and meat of 1 mg Cd kg FW⁻¹ (Stafford, Cavanagh, & Roberts, 2014). As a result, offal products grown in NZ from animals over 30 months of age are now discarded from the human food chain, due to Cd's bioaccumulation over time (Stafford et al., 2014). This issue poses reputational challenges to NZ's agricultural sector, and may provide grounds for trade barriers and tariffs preventing NZ offal exports to certain countries (Cavanagh, 2015; Loganathan et al., 2003).

NZ's land-use history is key to understanding why this issue has arisen, and why there is such spatial variation in Cd soil concentrations throughout NZ (Taylor et al., 2007). With the advent of topdressing in the 1940s began a long-standing trend of applying large amount of fertilisers – primarily superphosphate – to pastures to improve productivity and generate greater returns (Kim, 2005). However, the majority of NZ's phosphate rock used in the manufacture of superphosphate at this time was sourced from guano deposits in Nauru and Christmas Island, which contain the world's highest concentrations of Cd of 100 mg Cd kg phosphate rock⁻¹ (Alloway & Steinnes, 1999). Consequently, NZ superphosphate contained high Cd concentrations of up to 641 mg Cd kg P⁻¹ (Alloway & Steinnes, 1999). In response to this issue, the NZ fertiliser industry imposed voluntary limits on the Cd content of fertilisers of 340 mg Cd kg P⁻¹ in 1995, and dropped this limit again in 1997 to 280 mg Cd kg P⁻¹ (Cavanagh et al., 2013). Today, the majority of NZ's phosphate rock is sourced from Morocco, which contains approximately 38 mg Cd kg phosphate rock⁻¹, and produces P fertiliser of 240 mg Cd kg P⁻¹ (Alloway & Steinnes, 1999).

As Cd-containing fertilisers were historically applied to productive land areas, it is these areas today which have noticeable concentrations of Cd in soils.

Table 2 summarises mean soil concentrations of Cd for NZ land-uses (Cavanagh, 2014). It is observable here that land-uses which typically require large quantities of fertiliser inputs such as dairying and horticultural orchards exhibit higher soil Cd concentrations than other land-uses. Taylor et al. (2007) undertook an assessment of soil Cd concentrations throughout NZ, and determined native background levels to be 0.16 mg kg⁻¹. This was consistent across all areas and soil types. The national mean was 0.35 mg kg⁻¹, with a total range of 0-2.52 mg kg⁻¹ (Taylor et al., 2007). Figure 1 shows the soil Cd map of NZ produced by Taylor et al. (2007). This map, and Taylor et al.'s national mean, are consistent with findings by Cavanagh (2014) presented in Table 3. These findings highlight Waikato and Taranaki as having NZ's highest (0.74 mg kg⁻¹) and second highest (0.70 mg kg⁻¹) mean soil Cd concentrations respectively, with the Bay of Plenty a close third (0.58 mg kg⁻¹). This fits with expectations based on land-use, as these areas have histories of dairying and intensive agriculture. Canterbury and Otago exhibit the lowest national mean Cd concentrations in soil, 0.20 mg kg⁻¹, which is again reflective of past land-use and the lack of intensive agriculture in these regions (Cavanagh, 2014). Cd uptake into orchard plants and horticultural crops presents risks to human health, as ingestion of these plants as part of the human diet is a direct exposure pathway to humans (Golia et al., 2008). Thus it is horticultural sites which have been determined to have the most Cd associated risk within NZ's various agricultural sectors (Cavanagh et al., 2015).

Table 2. Summary of mean NZ Cd concentrations for varying land-uses sourced from Cavanagh (2014)

Land-use	Mean Cd soil concentration (mg kg ⁻¹)
Non-agricultural	0.13
Cropping	0.28
Drystock	0.33
Orchards	0.55
Dairy	0.59

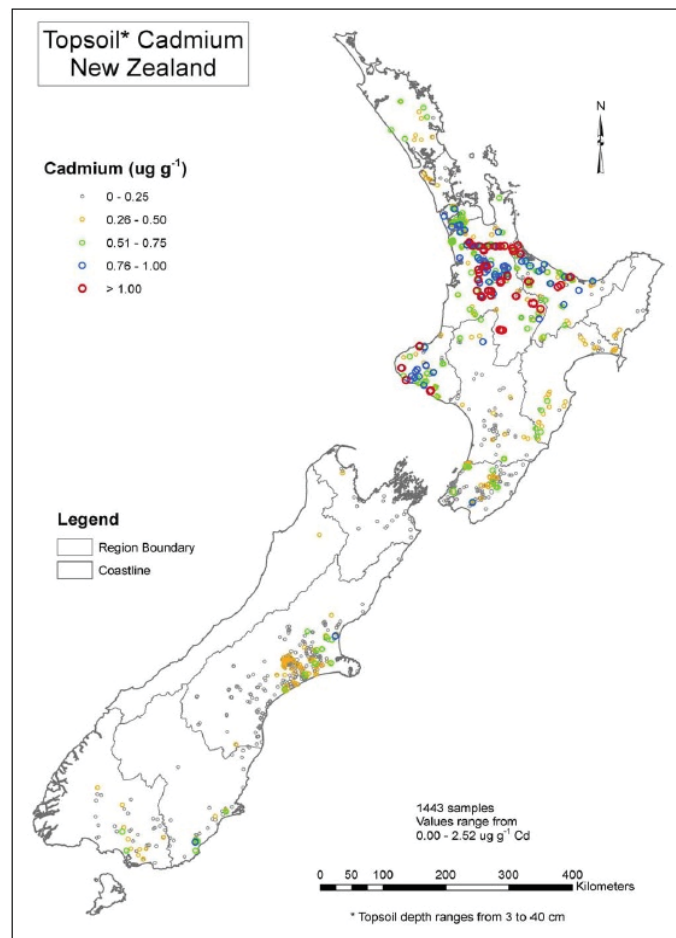


Figure 1. Topsoil Cd concentrations throughout NZ as determined by Taylor et al. (2007, p. 15). Note, concentrations here are presented in µg g⁻¹, equivalent to mg kg⁻¹ used elsewhere in this document.

Table 3. Summary of soil Cd concentrations throughout regions of NZ, as presented in Cavanagh (2014, p. 8)

Region	Median (mg kg ⁻¹)	Mean (mg kg ⁻¹)	Range (mg kg ⁻¹)
Northland	0.34	0.38	0.05-1.34
Auckland	0.35	.036	0.01-1.60
Waikato	0.74	0.74	0.01-2.05
Bay of Plenty	0.54	0.58	0.07-2.10
Gisborne	0.32	0.29	0.12-0.56
Hawke's Bay	0.27	0.31	0.06-0.80
Taranaki	0.71	0.70	0.06-2.14
Manawatu-Wanganui	0.26	0.33	0.00-1.06
Wellington	0.21	0.26	0.04-1.30
Tasman	0.33	0.40	0.04-2.04
Marlborough	0.24	0.28	0.03-1.02
Nelson	0.30	0.31	0.24-0.41
West Coast	0.11	0.20	0.00-0.71
Canterbury	0.17	0.20	0.02-1.33
Otago	0.20	0.20	0.00-0.59
National	0.32	0.44	0.00-2.14

2.5.2 Risks and Implications of Cadmium Accumulation for New Zealand

In general, Cd accumulation in NZ soils poses risks in three distinct areas: human health¹; trade; and land-use flexibility (Rys, 2011). Of most concern is the risk to trade: when Cd concentrations in produce (or meat) exceed international food safety guidelines, it becomes excluded from international markets, and thus represents a lost export market (Cavanagh, 2015). An example of this is offal products from animals >30 months old, which cannot be exported or consumed by humans, due to their Cd concentrations likely exceeding maximum permissible levels (Stafford et al., 2014). Cd concentrations in both wheat and potatoes grown in NZ have been found to exceed food standards, thus being labelled as non-compliant (Gray et al., 2001; Kim, 2005). Approximately 1.5% of potatoes grown in the Waikato region have been found to exceed such standards (Al Mamun et al., 2016b). Such non-compliance represents a risk to NZ's horticultural export market, currently worth \$4.3billion (Plant and Food Research, 2015). Vegetable produce constitutes approximately 6.9% of this total, worth \$621.2 million (Plant and Food Research, 2015). NZ's primary export vegetable markets are Australia and Japan, with significant exports also going to other Asian, European and Pacific nations (Plant and Food Research, 2015). These export markets are significant to the NZ economy, and face reputational risks when NZ products do not comply with Cd food standards. As such, it is a matter of national economic security to ensure the sustainability of this industry.

Risks to land-use flexibility can also result from Cd accumulation within soils. Cadmium is identified as a priority contaminant within NZ's *National Environmental Standard for Assessing and Managing Contaminants in Soil to Protect Human Health* (NES) (Ministry for the

¹Cadmium levels in NZ are not considered to impact human health (Vannoort & Thomson, 2011).

Environment, 2012), while the *Hazardous Activities and Industries List* (Ministry for the Environment, 2011) names it a hazardous substance. Table 4 details soil guideline values (SGVs) to protect human health for Cd for a range of land-uses presented in the NES. Thus, if a landowner wishes to convert contaminated agricultural land to residential use, they may be limited by the Cd concentration of the soil, and find that rural residential or residential 10% produce land-use is off limits due to high soil Cd concentrations (> 0.8 and >3 mg kg⁻¹ respectively). Therefore, although current soil concentrations may be below guideline values, continued application of P fertilisers will have impacts on future land-use flexibility for a number of sites in NZ.

Table 4. Soil contaminant standards for Cd determined to protect human health in NZ's NES

Land-use	Cd concentration (at pH 5) (mg kg DW ⁻¹)
Rural residential / lifestyle block 25% produce	0.8
Residential 10% produce	3
High-density residential	230
Recreation	400
Commercial / industrial outdoor worker (unpaved)	1,300

2.5.3 New Zealand's Cadmium Management Strategy

In response to the issue of Cd accumulation in NZ, the Cadmium Working Group (now the Cadmium Management Group) was established in 2006 by the Chief Executives Environmental Forum, involving representatives from many stakeholder groups (Rys, 2011). These include the Fertiliser Association of NZ, NZ Food Safety Authority, Fonterra, Dairy NZ, Beef and Lamb NZ, Horticulture NZ, the Foundation of Arable Research, Regional Councils, the Ministry for the Environment, and the Ministry for Primary Industries (MPI) (Environment Waikato, 2008; Rys, 2011). In 2011 this group released the *National Cadmium Management Strategy* (NCMS), which aimed to address the range of risks caused by Cd contamination of NZ's agricultural soils with a risk-based approach to Cd management (Cadmium Working Group, 2011). This report was internationally reviewed prior to its publication (Warne, 2011). A key part of this document was the introduction of the *Tiered Fertiliser Management System* (TFMS), which aims to control and restrict Cd accumulation, and minimise risks to human health, trade, land-use flexibility and environmental integrity with regard to Cd in soils over the following 100 years (Cavanagh et al., 2013). The TFMS links soil Cd concentrations to management actions, with a tiered structure of increasing Cd levels as shown in Table 5 (Rys, 2011). This system is implemented by the fertiliser industry with testing done as part of routine soil assessments on farms, and enforces increasingly stringent controls on P fertiliser use (application rate and type) as tiered Cd concentrations increase (Stafford et al., 2014). Appropriate management practices to lower Cd phytoavailability must also be implemented at and above Tier 1, including alleviating soil Zn deficiencies,

maintaining an appropriate soil pH, and maintaining a high OM content (Sneath, 2015). At Tier 4, no further Cd accumulation is permitted within soils, unless a site specific investigation is undertaken to assess risks and potential exposure pathways (Sneath, 2015).

Table 5. Representation of the Tiered Fertiliser Management System from Cavanagh (2012, p. 1), showing tiers, trigger values, and required management actions

Tier	Management Action Required	Cd Concentration (mg kg⁻¹)	Trigger Value (mg kg⁻¹)
0	Five-yearly screening soil test for Cd status	0-0.6	0.6
1	Application is restricted to a set products and application rates to minimise accumulation, and landholders are required to test for Cd every five years using approved programmes	>0.6-1.0	1.0
2	Application rates are further managed by use of a Cd balance programme to ensure that Cd does not exceed an acceptable threshold within the next 50 years	>1.0-1.4	1.4
3	Application rates are further managed by use of a Cd balance programme to ensure that Cd does not exceed an acceptable threshold within the next 50 years	>1.4-1.8	1.8
4	No further accumulation over the trigger value	>1.8	

The TFMS trigger values are derived from both NZ and international research with internationally sought and reviewed expert recommendations (Cavanagh, 2012; Warne, 2011). Sources of these trigger values include NZ's background soil Cd levels (Tier 0); NZ biosolids guidelines (Tier 1); Canadian agricultural SGVs for human and ecological health (Tier 2); and United Kingdom SGVs for allotments (Tier 3) (Cavanagh, 2012). International data was used here due to a lack of NZ specific information (M. Taylor, personal communication, September 10, 2015). The system is designed so that Cd concentrations should take more than 100 years to progress from Tier 1-4 (Sneath, 2015). However, due to their absolute nature and their international derivations, the TFMS trigger values do not account for site specific variations in background levels, or soil and plant specific factors which influence Cd plant uptake (McDowell, Taylor, & Stevenson, 2013). Under this system, total Cd concentrations are considered rather than phytoavailable Cd, and thus risk and potential exposure through the food chain may be overestimated (Cavanagh et al., 2015). As such, the efficacy of the TFMS trigger values may be improved by foundations of site specific relationships between soil factors and plant uptake (Cavanagh et al., 2015). There is a current lack of research here concerning NZ specific Cd related risk to agricultural systems and the capacity for management of these risks (Cavanagh et al., 2015). The NCMS and in particular the TFMS trigger values are due to be reviewed in 2017 with

the intention of implementing NZ soil and crop specific trigger values, thus engendering a risk-based strategy for Cd management (Cavanagh et al., 2013; McDowell et al., 2013).

As well as the TFMS, the NCMS implemented a number of work programmes to address the range of risks posed by Cd accumulation in NZ. These include: food monitoring (including the NZ Total Diet Survey); environmental monitoring and research; and education and management concerning the risks and causes of Cd accumulation (Cadmium Working Group, 2011). The upcoming review of the NCMS will also assess new relevant research and information, as well as its efficacy at managing Cd related risk and providing governance (Rys, 2011). Thus, the NCMS remains a strategy under development.

2.6 Mitigations for Cadmium Plant Uptake

2.6.1 Organic Amendments

Management practices which decrease Cd phytoavailability in soils may be further developed to become mitigation strategies for this issue. As identified in previous sections, the OM content of soils is a primary factor influencing Cd's phytoavailability. As OM content increases, plant uptake of Cd decreases thus it is beneficial to increase the soil's OM content in order to immobilise and contain Cd within the soil matrix (Roberts, 2014). OM content can be increased with the application of a range of organic amendments including compost, peat, manure, animal and plant waste, biosolids, lignite, biochar and sawdust.

In a pot experiment by He and Singh (1993), OM was added to soils in the form of sphagnum peat as part of a study to determine the effects of OM content on Cd plant uptake. This study also addressed OM's effect on the distribution and extractability of soil Cd. Results showed that addition of OM decreased Cd plant uptake in ryegrass, with no effect on DM yield. Cadmium plant uptake decreased with increasing applications of OM, with the highest reductions in plant uptake occurring in sandy soils. Ryegrass grown in sandy loam and clay loam soils underwent decreased Cd uptake with OM additions, however this decrease was less than that observed in the sandy soil. This demonstrates the existence of soil specific factors which intersect to influence Cd plant uptake. The authors conclude that the effect of OM was due to resultant increases in the soil's CEC.

In Cieccko et al.'s (2001) investigation of the effects of OM and liming on Cd uptake in triticale and spring oilseed rape, both brown coal (lignite) and compost amendments were used to test the effects of OM on Cd plant concentration and yield. This involved a pot experiment conducted in a greenhouse on Polish soils which were artificially contaminated with Cd. Cieccko et al. found that crops grown in soils with no added OM or lime (60% oxide lime) had a

significantly reduced yield due to Cd contamination, however this effect was neutralised when lignite or compost was added. Furthermore, decreases in Cd content of triticale tissues of several percent occurred with application of compost or lignite, with compost producing larger decreases. Liming produced further, though relatively smaller, reductions in Cd content of triticale grain, and limited the yield reductions observed as a result of Cd toxicity to oilseed rape. Similarly, Gambus and Gorch (1996) showed that manure application decreased the Cd content in above-ground portions of oat crops by 24% when used as an organic amendment.

Bolan, Adriano, Duraisamy, and Mani (2003) investigated the effect of biosolid compost on Cd immobilisation and phytoavailability in two variable charge soils from NZ (Egmont and Manawatu). The effect of biosolid compost on Cd uptake was also tested on Manawatu soil. The compost was produced by commercial compost company Living Earth. This glasshouse experiment involved Indian mustard (*Brassica juncea* L.) plants grown in artificially contaminated soils. Additions of the compost increased the negative charge of the soils, and decreased the labile Cd content (NH₄OAc extractable Cd and soil solution Cd). Sorbed Cd remained in soils in the form of organic complexes. Biosolid compost increased the DM yield of Indian mustard with increasing application rates, and decreased Cd uptake with more pronounced effects at higher soil Cd concentrations. Thus, Bolan, Adriano, Duraisamy, et al. (2003) conclude that biosolid compost amendments show potential in decreasing the phytoavailability of Cd in agricultural soils.

The role of lignite as a Cd fixing amendment was explored by Simmler et al. (2013) in a pot experiment. Ryegrass (*Lolium perenne* L.) was grown in spiked alluvial soil, with Cd concentrations of 0 mg kg⁻¹ (unspiked), 1.1 mg kg⁻¹ (added in the form of CdSO₄ solution), or at 3.7 % wt equivalent by blending soil with 10% biosolids. Undried lignite was added at rates equivalent to DW concentrations of 0, 1.0, 3.4, and 7.1 % wt. Lime was added to a second treatment series at 65 g per plot to assess the effects of this additive at decreasing Cd solubility by altering soil pH and increasing competition for root surface exchange sites between Cd²⁺ and Ca²⁺. In the treatment series without lime addition, lignite reduced Ca(NO₃)₂ extractable Cd concentrations and ryegrass uptake by up to 52%. When lime was applied, lignite amendments at 3.4 % wt reduced plant uptake of Cd – although at a lesser rate than treatments without lime – however did not reduce Ca(NO₃)₂ extractable Cd concentrations. Thus the effect of lignite in reducing plant uptake of Cd is weaker at a higher pH. Lignite additions of up to 3.4 % wt had no impact on pasture yield, however at 7.1 % wt decreased yield by 10-20%. The authors recommend amendments of 1 % wt lignite (equivalent 23.2 t ha⁻¹ with a soil density of 1.2 g cm³ ⁻¹) as a possible in situ fixation treatment for Cd in agricultural soils, however assert that the efficacy of such a treatment is likely to vary with soil type.

A range of organic amendments were tested for their capacity to inhibit plant uptake in a batch sorption experiment and pot trial by Al Mamun et al. (2016a). The batch sorption experiment involved spiking 0.05 M Ca(NO₃)₂ solution with CdSO₄ solution to produce Cd concentrations of 0, 1.4, 6.8, 13.2, 18.9 and 24.5 mg L⁻¹. Zeolite powder, charcoal, sawdust, bentonite, biosolids, lignite, two kinds of compost (Living Earth municipal green waste and Parkhouse sawdust and animal residues), and two NZ soils (Levin and Pukekohe) were added to spiked samples. The pH was then adjusted to a range of target pH values. Cadmium adsorption coefficients (K_d) were determined for each amendment, and are presented in Figure 2. In general, Cd adsorption decreased as pH decreased for all amendments. The two composts and lignite exhibited the greatest capacity for Cd binding at a range of pH values. From these results, lignite and Living Earth compost (due to its lower price than Parkhouse compost – \$12 t⁻¹ c.f. \$100 t⁻¹) were selected for a pot trial experiment assessing the role of these amendments in reducing Cd plant uptake. Onions (*Allium cepa* L. var. Pukekohe long keeper), spinach (*Spinacia oleracea* L.) and lettuce (*Lactuca sativa* L. var. Buttercrunch) were grown in Pukekohe and Levin soils with amendments added at rates of 1.05% and 2.63% lignite (referred to as 1% and 2.5% respectively), and 2.7% (w/w) compost (referred to as 2.5%). The compost treatment produced reductions in Cd uptake of >20% for all crops in both soils. This is attributed to increased cation exchange and the significant Zn content of the compost. Lignite was less effective at reducing Cd transfer from soil to plant, with the 2.5% treatment reducing plant concentrations by ≥10% in the Levin soil. In the Pukekohe soil, however, onions and spinach showed no significant decreases while lettuce showed increased concentrations of Cd as a result of 2.5% lignite addition. The 1% lignite addition reduced Cd concentrations by 28-34% in all scenarios except spinach grown on Pukekohe soil. Compost was determined as the most effective and consistent amendment for reducing Cd plant uptake. Compost had no impact on plant yield or other micronutrient uptake, and was judged an economic option, at costs of \$975 ha⁻¹.

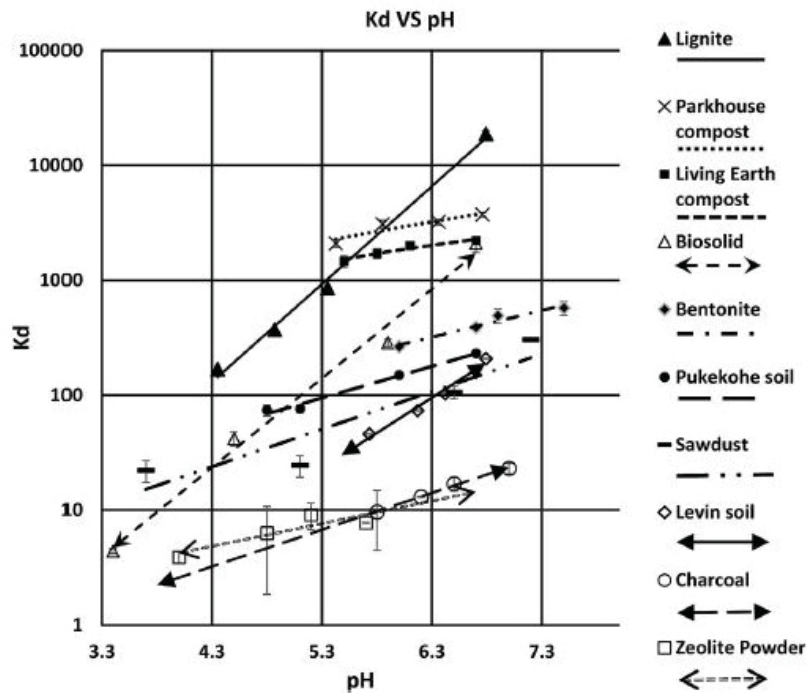


Figure 2. K_d values of organic amendments and soils through a range of pH values, produced by Al Mamun et al. (2016a). Error bars show the standard error of the mean ($n = 3$)

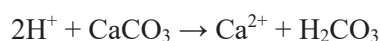
2.6.1.1 Compost

From the study described above by Al Mamun et al. (2016a), the use of compost amendments was determined to be a potential mitigation for Cd contaminated land. Studies by Cieccko et al. (2001) and Bolan, Adriano, Duraisamy, et al. (2003) also support this assertion. As there are many forms of compost, Al Mamun et al. chose the most economic option, municipal greenwaste compost from Living Earth, NZ. This compost is available for a cost of \$12.50 t^{-1} and is sourced from Christchurch, a close distance to Lincoln University where these experiments were conducted (G. Wright, personal communication, November 22nd, 2016). The impact of municipal Living Earth compost in intensive vegetable rotations on soil health indicators, yield, and financial viability was also previously assessed in a field trial in North Christchurch from 2009-2012 (Horrocks, Tregurtha, Maley, & Meenken, 2013). A cropping rotation using three crops (lettuce December 2010-February 2011; cabbage March 2011-August 2011; lettuce December 2012-February 2012) was established, with compost applied in one-off applications at rates of 14 and 28 $t ha^{-1}$. Chicken manure was also applied in different treatments at a rate of 10 $t ha^{-1}$. Amendments were soil-incorporated, and all trial plots continued to receive equal fertilisation throughout the trial typical of intensive vegetable production sites. Fertiliser supplied 331 kg N ha^{-1} , 44 kg P ha^{-1} , 123 kg K ha^{-1} , 67 kg S ha^{-1} , 34 Ca ha^{-1} and 17 kg Mg ha^{-1} to each plot. Both the compost and chicken manure contained essential plant nutrients supplied in fertiliser, with compost containing 14 kg total N t^{-1} , 23 kg total P t^{-1} , 48 kg K t^{-1} , 30 kg S t^{-1} , 155 kg Ca t^{-1} and 22

kg Mg t⁻¹. The pH of the compost was 6.8. Results showed that no effects on yield were observed as plots continued to receive high fertiliser inputs, and thus the authors suggest that quantifiable fertiliser reductions should be calculated to offset nutrients available from compost. This may translate to economic benefits in reduced fertiliser requirements. Crops showed an increased ability to respond to N from soil, fertiliser and compost when compost was applied. However, the assertion is made that N fertiliser application should not be substituted with compost, only reduced. Compost addition resulted in increased levels of N, P, K and particulate OM in soils for prolonged amounts of time post-trial, and thus may provide benefits to soil fertility and crop nutrient requirements, benefitting subsequent crop rotations without the need for further compost addition. Soil OM and C content were also significantly increased with compost addition. Furthermore, with high rates of compost addition, soil structure and water holding capacity showed improvement. While this study did not address Cd immobilisation by compost OM, it demonstrated the beneficial effects of compost in vegetable production. Thus, there are likely to be benefits above and beyond those concerning Cd when compost is applied to horticultural production systems.

2.6.2 Lime

Lime is applied to agricultural soils primarily to increase pH due to its alkaline nature (Sime, 2001). The most common form of lime is CaCO₃ (aglime), however Ca(OH)₂ (slaked lime or hydrated lime), CaO (quicklime), and CaMg(CO₃)₂ (dolomite lime) are also commonly used in agricultural practices (Sime, 2001). Liming is a routine practice in many pastoral systems, as it has benefits including stimulation of clover and other legume growth, increased pasture production, encouragement of even grazing, increasing the availability of plant nutrients at optimal pH values and alleviation of Al toxicity (Sime, 2001). Its main benefit of remediating soil acidity is a result of two processes: displacement of acidic H⁺ ions by Ca²⁺ in the soil; and reactions between CaCO₃ (in the case of aglime) and H⁺ to form carbonic acid (H₂CO₃) and Ca²⁺. H₂CO₃ then breaks down to form H₂O and CO₂ (Sime, 2001). This is expressed by the equations:



A lime application of 2.5 t ha⁻¹ will remain in soils creating noticeable pH changes for at least six years (Sime, 2001). Nutrient availability is affected by soil pH, in the same way as Cd phytoavailability. A pH range of 6-7 provides ideal conditions for major nutrients N, P, K and S as well as Mg and Ca (Sime, 2001). As for crops, wheat prefers a pH range of 5.5-6.5, lettuce prefers 6.7-7.0 and potatoes prefer 4.8-6.5 for optimal growing conditions (Sime, 2001). However, lime may also reduce crop yields if it is applied in very high quantities, or if soil pH is

improperly adjusted (Ciecko et al., 2001). Ciecko et al. (2001) reported that lime applications negatively affected triticale root development, and resulted in a lower triticale yield than treatments without lime application. Similarly, Rogoz (1996) reported that lime application reduced the yield of both roots and aboveground portions of maize crops.

As well as influencing Cd phytoavailability by changing soil pH, lime also adds Ca^{2+} to soils, which competes with Cd^{2+} for root surface exchange sites (Simmler et al., 2013). This generally decreases Cd plant uptake. Bolan, Adriano, Mani, et al. (2003) give several explanations for lime induced immobilisation of Cd: increases in CEC in soils with variable charge components; metal precipitation as hydroxides; the formation of hydroxyl metal species; and augmented microbial activity leading to sequestration. In some cases, however, if lime is not adequately applied to sufficiently alter pH and increase Cd sorption (thus immobilising the trace element), the Ca^{2+} added via lime may compete with Cd^{2+} for soil sorption sites, and thus increase the concentration of Cd^{2+} in soil solution (Bolan, Adriano, Mani, et al., 2003; Loganathan et al., 2012; Simmler et al., 2013). This has the undesired effect of increasing Cd phytoavailability. Raw limestone may also have a Cd content of up to 5 mg kg^{-1} , thus lime applied to soils may increase the total soil Cd content (Sime, 2001). However, this low concentration is unlikely to have a noticeable effect on soil Cd status.

In studies described above by both Ciecko et al. (2001) and Simmler et al. (2013), the effect of lime on Cd plant uptake has been addressed through pot trial experiments. A further study by Bolan, Adriano, Mani, et al. (2003) assessed the effects of $\text{Ca}(\text{OH})_2$ and KOH on Cd sorption in two soils (NZ Egmont and Tokomaru soil). $\text{Ca}(\text{OH})_2$ was used to assess the effects of lime, while KOH was used to delineate between the effects of increased pH and increased Ca^{2+} concentrations on Cd adsorption. These amendments were added at rates sufficient to achieve a target pH range of 5.2-7.9. These alkaline amendments increased the soil pH and thus increased Cd adsorption, with KOH producing the greatest increase in adsorption. This is explained by increased adsorption competition from Ca^{2+} with Cd^{2+} in soils with $\text{Ca}(\text{OH})_2$ addition. $\text{Ca}(\text{OH})_2$ was found to reduce extractable and soluble Cd, but increase inorganically-bound Cd fractions in soil. The authors conclude that the decreases in phytoavailability are primarily due to pH-induced increases in the soil's negative charge, and the resultant immobilisation of Cd within the soil. Bolan, Adriano, Mani, et al. (2003) further investigated the impact of $\text{Ca}(\text{OH})_2$ on plant uptake of Cd in a glasshouse experiment using Indian mustard (*Brassica juncea* L.). They found here that uptake decreased with increasing pH (as a result of higher rates of $\text{Ca}(\text{OH})_2$ addition), however DM yield decreased with the highest rate of addition. Thus lime has been found to have beneficial effects on Cd phytoavailability, by reducing bioavailable fractions within soil due to its impact on soil pH. A number of other studies have observed the effects of lime application on soil Cd and plant uptake. Table 6 lists many of these, detailing the type of liming material used,

the application rates, and the primary observations. Common trends from these studies include decreased Cd concentrations in soil solution and plant tissues with the addition of liming materials, however one study by John, Van Laerhoven, and Chuah (1972) found that plant uptake of Cd tended to increase at low lime application rates but decrease at higher rates of application.

Table 6. Studies assessing the effects of lime on soil and plant Cd, with application rates and primary observations

Lime Material	Author	Application Rate Range	Primary Observations
CaCO ₃	Bingham, Page, Mitchell, and Strong (1979)	10 g kg ⁻¹	Cd phytotoxicity was decreased in wheat
	Brown, Chaney, and Angle (1997)	2.1–45 t ha ⁻¹	Relatively less Cd mobility compared with Cu and Zn
	Fernandes, Abreu, Calouro, and Vaz (1999)	0–4.5 g kg ⁻¹	Decreased CaCl ₂ and NH ₄ OAc extractable Cd (1999)
	Han and Lee (1996)	0–20 g kg ⁻¹	Cd in soil and plant tissue Cd decreases in Cd concentration of plant tissue
	He and Singh (1994)	0–5.226 g kg ⁻¹	Decreases in Cd concentration of plant tissue
	John, Van Laerhoven, and Chuah (1972)	0–1000 mg kg ⁻¹	At low application rates, increased plant Cd; at high application rates, decreased plant Cd
	John and Van Laerhoven (1976)	17.92 t ha ⁻¹	Decreased Cd plant uptake
	Lehoczky, Marth, Szabados, and Szomolanyi (2000)	0–10 g kg ⁻¹	Decreased Cd uptake in lettuce
	Maclean (1976)	3000 kg ha ⁻¹	Decreases in extractable Cd in soils, and total Cd in plant tissues
	Maier et al. (1997)	0–20 t ha ⁻¹	Increased Cd concentrations in potato tubers
	Oliver et al. (1996)	0–2.5 t ha ⁻¹	Decreased Cd content of barley grain
	Singh and Myhr (1998)	-	Decreases in extractable soil Cd; increases in plant Cd concentrations
	Ca(OH) ₂	Singh, Narwal, Jeng, and Almas (1995)	1–5 g kg ⁻¹
Brallier, Harrison, Henry, and Dongsen (1996)		8, 15 and 22 t ha ⁻¹	Decreased Cd in soil solution and plant uptake of Cd
Gray et al. (1999b)		To achieve pH values 5.5, 6.0, 7.0	Decreased extractable Cd concentrations, and decreases in plant Cd concentrations
CaCO ₃ and Ca(OH) ₂	Chaney, Strickland, and Lamoreaux (1977)	0–1120 kg ha ⁻¹	Decreased Cd phytotoxicity
CaMgCO ₃	Kreutzer (1995)	4 t ha ⁻¹	Decreased Cd concentrations in soil solution

2.6.2.1 Soil pH Buffering Capacity

When soil pH is adjusted as in the case with lime addition, soil has a capacity to resist this change (Sime, 2001). This is known as the soil's pH buffering capacity, and is a function of the soil's CEC (Sime, 2001). As lime neutralises soil, it neutralises H^+ ions both in soil solution and adsorbed to soil colloids. Thus more $CaCO_3$ will be required than can be estimated from the soil pH, or the amount of H^+ within soil solution (Sime, 2001). More lime is required to increase pH in soils with higher CECs (Sime, 2001). The buffering capacity determines the amount of lime needed to achieve a target pH (Rogovska & Blackmer, n.d.). Buffering capacity can be calculated using a pH buffer curve. Here, buffer solutions of known pH are mixed with soil, and the changes in pH are then measured once there has been sufficient time for equilibration (Hill, Mallarino, & Pagani, 2009). Small pH changes represent a high buffering capacity and need for greater quantities of lime or acid, while large pH changes represent a lower buffering capacity and need for less lime or acid amendments to achieve desired pH (Rogovska & Blackmer, n.d.).

When pH buffer curves are developed in laboratory situations they generally do not translate directly to field situations. As buffer curves are generated within 24 hours, they tend to underestimate the amount of lime or acidic amendments required to adequately alter pH as the soil has less time in which to reach an equilibrium (Ketterings, Rao, Dietzel, & Ristow, 2010). This makes producing a targeted pH value difficult in a field situation, as no clear framework exists in which to quickly and accurately achieve this. Thus, the derivation of a framework with which to rapidly and economically convert pH buffer curve results to in-field amendment rates that could be used by farmers to accurately alter soil pH would represent an innovative step in soil pH management.

2.7 Environmental Management of Cadmium in New Zealand Soils

Although environmental science determines the concentration and flux of contaminants in soil, it does not assess the cost, practicality and applicability of mitigation techniques within the context of regulation. In order to determine an effective mitigation strategy, several practical aspects must be considered. Mitigations should be low-cost and leave the soil in a fertile state so productive land-use may continue (Simmler et al., 2013). In situ fixation of Cd, primarily using soil amendments, represents one such possibility. Impacts on crop growth, yield and interaction of amendments with soil characteristics may then need to be considered in this context. Mitigations also need to fit within current policy and regulation frameworks, to ensure ease of implementation within the wider industry.

Economic viability represents perhaps the most important factor in determining a practicable mitigation strategy for soil Cd in NZ. Concerning soil amendment use, costs are

incurred during the purchasing, transportation, and application (in the form of labour) of these amendments. To be economically viable, the implementation of a strategy must cost less than the resulting benefits (Department of Finance, 1991). One such way to determine this is through the use of cost-benefit analysis (CBA) which compares costs and benefits associated with a project or strategy and determines the overall net return (Department of Finance, 1991). Cost-benefit analyses are particularly useful for environmental and agricultural projects, as they take into consideration social and environmental factors which would otherwise be externalised due to their lack of an assigned monetary value (Department of Finance, 1991).

Practicality, availability and acceptability are further managerial aspects concerning the use of soil amendments to reduce Cd phytoavailability. If amendments are to be used on a national scale to remediate Cd contamination of horticultural soils, there must be a sufficient, consistent supply which can keep up with this high level of demand. Amendments must also be practical to apply and able to fit in with routine agronomic practices. If significant effort (and thus increased labour costs) is involved with application, there may be resistance to this strategy from target populations. Furthermore, target populations must accept the use of particular amendments, and thus potential barriers to adoption must be identified. Such barriers may include pre-existing perceptions; inconsistencies of, or potential issues arising from, the use of amendments; and reluctance among growers to implement new, potentially costly management practices. Opening up discussions with relevant stakeholders may garner a better insight into these potential issues and their significance, and ways in which they may be minimised.

2.8 Current Cadmium Research in New Zealand

Considering the opportunity to mitigate risks with simple soil amendments, and the knowledge gaps that exist in implementing such a strategy, research was undertaken within NZ to better understand the soil and plant specific characteristics responsible for Cd plant uptake, as this has been shown to be non-uniform throughout NZ soils. This research forms part of a wider project which addresses current and future risks within NZ's agricultural industry posed by Cd accumulation as a result of fertiliser use on productive soils (Cavanagh, 2015). This wider project is funded by the Fertiliser Association of NZ and will help to inform the upcoming review of NZ's National Cd Management Strategy taking place in 2018 (Cavanagh, 2015). Specific aims of this research (detailed in Cavanagh (2015)) include:

1. Determination of relationships between soil properties and Cd uptake of particular crops, in order to ensure food standard compliance of horticultural produce by establishing SGVs for food standard protection. The efficacy of potential mitigations will also be assessed. This research includes field surveys of Cd concentrations in particular cultivars of wheat, onions, spinach and

potatoes grown in a range of soils representative of commercial horticultural soils in NZ; field trials in which the role of lime and compost in reducing Cd plant uptake are assessed, and this mitigation strategy's efficacy determined; and investigation of the role of metal oxides and clay mineralogy in Cd plant uptake in soils which exhibit Cd uptake levels independent of soil pH and OM content.

2. Providing data which will lead to the development of SGVs for the purposes of protecting livestock product food standards. This will entail investigation of soil properties which drive Cd uptake in pasture species including forage crops such as plantain and chicory. Liver biopsies of livestock will be used to assess the validity of existing models for Cd bioaccumulation in livestock.

3. Investigation of Cd's role in toxicity to soil rhizobia and white clover (particularly implications for N₂ fixation and legume:clover symbiosis). This will lead to the establishment of guidelines for soil Cd concentrations to protect pasture quality and productivity.

2.9 Research objectives

Of the abovementioned research, the area of interest for this current work is in the field trials to assess the role of lime and compost at reducing Cd plant uptake and determine the validity of this potential mitigation. Within these field trials, four sites in NZ have been chosen as representative soils for horticultural production, and potato and wheat plots established. At the commencement of the field trials, soils are to be amended with differing treatments of lime, S and compost, with the aim of manipulating soil pH and OM content to regulate Cd bioavailability. Application rates for lime and S need to be determined in order to reach a series of target pH values at each site. This is a focus of the current work, involving assessment of the soils' buffering capacity and the translation of this data into field applicable amendment rates. To place this work within the context of environmental management, the validity of this mitigation strategy requires consideration. This involves assessing the strategy's economic viability through the use of CBA, and considering practical aspects of the implementation of this strategy. The regulatory context in which this strategy would be employed should also be considered, to provide recommendations for successful implementation.

2.9.1 Current Research Aims

Aim 1: To characterise these soils, and assess the relative risk of Cd plant uptake at these sites. This data will provide a baseline for which to compare soil data both post-amendment application and at the conclusion of the field trials.

Aim 2: To calculate necessary lime and S amendment application rates to ascertain a range of target pH values within these soils. The determination of a factor by which to convert laboratory generated pH buffer data to in-field application rates is a further aim, as this represents an innovative step for pH management in NZ soils.

Aim 3: To place this work within an environmental management context. This includes determining the economic viability of the proposed mitigation strategy using lime and compost amendments through a CBA, and assessing the implications and factors relating to the implementation of this strategy on a national scale. Furthermore, to provide recommendations for implementation of this mitigation in the context of the relevant regulatory framework.

3 Site Characterisation – Introduction to Study Farms

To undertake field trials assessing the role of lime and compost soil amendments in reducing Cd bioavailability and lowering plant uptake, four sites throughout NZ were selected as study farms. These sites were selected to provide a range of soil types and characteristics typical of horticultural areas throughout different locations of NZ. A pre-amendment analysis was conducted on these soils, in order to determine baseline levels for soil parameters. This included analysis of total Cd, exchangeable Cd, pH, OM content, CEC, total Zn, exchangeable Zn, Al and Fe oxides (through acid oxalate extraction), total P and total N at each site.

3.1 Materials and Methods

3.1.1 Soils and Sampling

Four horticultural production sites throughout NZ were used as part of the current research to assess the efficacy of lime and compost at reducing plant uptake of Cd (See Figure 3). The first site was located on a commercial plot in Pukekawa in the North Island, and was used for potato production. The soil here was a clayey orthic granular soil, formed from weathering of volcanic material (Landcare Research, 2017). The second site was also used for potato production, and was located in the North Island near Palmerston North at AgResearch's Aorangi farm. This site contained Kairanga silty clay, a typical orthic gley soil. The final site was located in Lincoln in the South Island on a Plant & Food research farm. Here both wheat and potatoes were cultivated on adjacent sites. This site contained a pale coloured typical immature pallic soil. Each site contained 30 plots, with potato plots measuring 4 x 3.4 m, while the wheat plots measured 3 x 1.65 m.

For the purposes of initial site characterisation, six cores were collected and bulked from each individual plot (a total of 180 cores per site). These samples were collected within the 24 hours prior to lime and compost amendment application. All soils were air dried at 35-40°C and sieved to 2 mm prior to analysis.

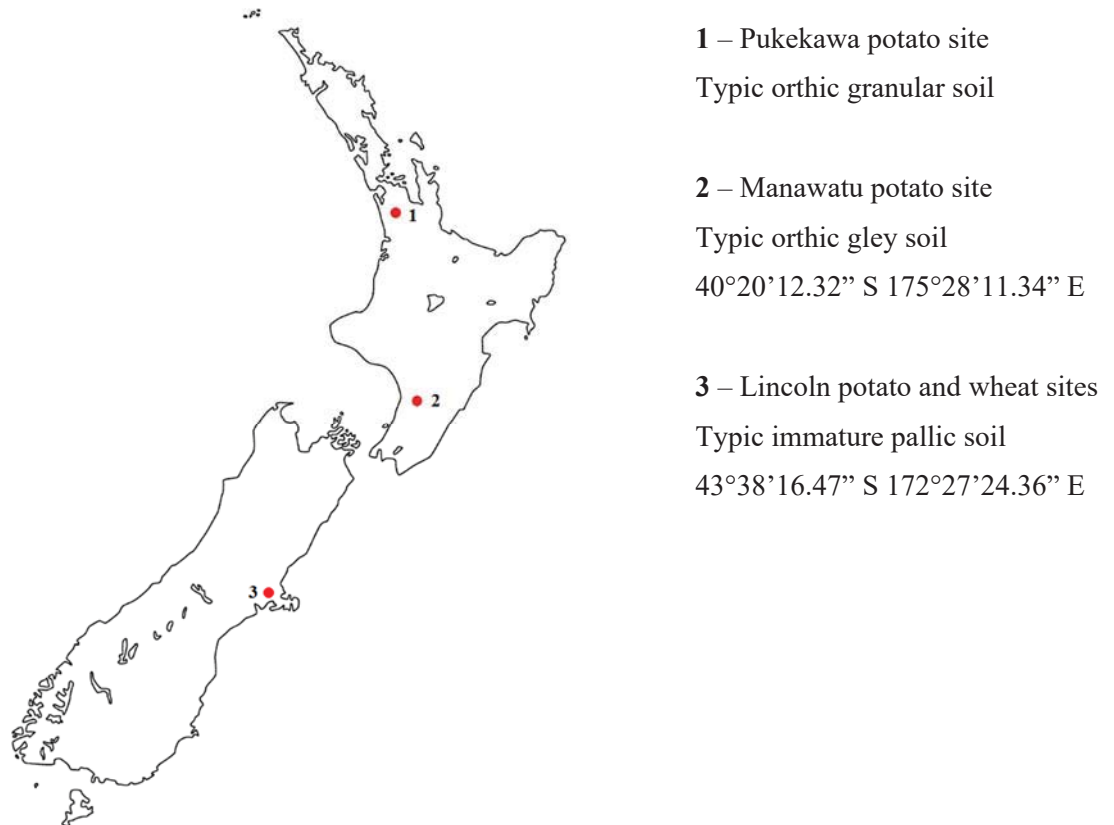


Figure 3. Location of horticultural soil sites used. Soil types at each site are detailed in the map legend according to the NZ Soil Classification.

3.1.2 Soil Characterisation (Pre-amendment Analysis) Methods:

3.1.2.1 Total Cadmium, Zinc and Phosphorus

Following a wet digestion method for the total concentrations of elements like that described by Kovács, Prokisch, Györi, Kovács, and Palencsár (2000), total Cd, Zn and P were measured via digestion with aqua regia (HCl:HNO₃=3:1 (v/v)), whereby 1 g (±0.1g) of soil was weighed into digestion tubes, and 10 mL aqua regia was then added. Tubes were left to predigest overnight at room temperature. Following this, tubes were placed into a digestion block and digested for approximately five hours, with a start temperature of 60°C. The temperature was increased in 20°C increments every 15 minutes until the temperature reached 120°C, then maintained for four hours. Small glass funnels were inserted into digestion tubes in order to allow reflux. After completion of digestion, the funnels were removed and the temperature was increased to 150°C over the course of 30 minutes to evaporate the excess acid in the tubes until approximately 1 mL of solution remained. The remaining sample was then diluted to 50 mL with deionised water, and mixed using a Thermolyne Maxi Mix II (M37615) vortex mixer before being filtered through Whatman 42 filter paper. Samples were then analysed through an Agilent 4200 Microwave Plasma-Atomic Emission Spectrometer (MP-AES) to ascertain total Zn, while total Cd for the

Manawatu site was analysed using a Perkin-Elmer AAnalyst 600 Graphite Furnace Atomic Absorption Spectrophotometer (GFAAS). Total Cd for Pukekawa, Lincoln Potato and Lincoln Wheat soils was analysed by Hill Laboratories via Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Total P was analysed using the Murphy and Riley phosphomolybdate method on an autosampler (Blakemore, Searle, & Daly, 1987).

3.1.2.2 Exchangeable Cadmium and Zinc

Several methodologies exist for the determination of plant available micronutrients, in particular Cd and Zn. These include using chemical extractants which are neutral or non-chelating, including 0.05 M Ca(NO₃)₂, 0.01 or 0.05 M CaCl₂, or 1 M NH₄OAc (pH 7) (Loganathan et al., 2003). The 0.05 M Ca(NO₃)₂ method was chosen in order to standardise methods across laboratories involved in different stages of analysis throughout this project (that is, soil analysis at time of pre- and post-amendment, and at time of harvest). This followed the methodology of McLaren, Clucas, and Taylor (2005) whereby 5 g of soil was weighed into 50 mL Oak Ridge centrifuge tubes, with 30 mL of 0.05 M Ca(NO₃)₂ added. Two blanks containing only 0.05 M Ca(NO₃)₂ were also used. Samples were placed in an end-over-end shaker and left for two hours, before being centrifuged at 1,068 g for 10 minutes. Samples were then filtered through Whatman 42 filter paper and stored at <4°C before being analysed through MP-AES for Zn, while Cd samples were sent to Hill Laboratories for analysis via ICP-MS.

3.1.2.3 pH

Soil pH was measured with use of a pH electrode, at a soil:water ratio of 1:2.5. Five g of soil was weighed into pH beakers, with 12.5 mL of deionised water added. Samples were stirred vigorously for at least one minute, before being left to sit for a minimum of 16 hours. Samples were then restirred, and the pH measurement taken using a Hanna HI 2211 Microprocessor-based pH/mV/°C bench pH meter.

3.1.2.4 Total Nitrogen, Organic Carbon and Organic Matter Content

Soil total N and C were analysed using a vario MACRO cube CHNS elemental analyser (Elementar Analysensysteme GmbH, Hanau, Germany). Organic C was then multiplied by a factor of two to obtain OM content, using the assertion of Pribyl (2010) that C constitutes 50% of soil OM.

3.1.2.5 Cation Exchange Capacity

Soil CEC was analysed following the semi-micro leaching technique described in Blakemore et al. (1987). Here 1.00 g of soil was mixed homogeneously by hand with approximately 3 g of analytical sand and poured into leaching tubes blocked with dampened Whatman 541 filter paper. Two blanks containing only analytical sand were included. Tubes were placed into a manifold and leached with 1M ammonium acetate (pH 7 ± 0.05) at a rate of 1 mL per minute for 45 minutes. Leachates were then topped up to 50 mL by weight with 1M ammonium acetate and the pH taken with a pH electrode. Samples were then spiked with 2 mL of 26,000 ppm Sr, Cs solution to keep the samples at 1000 ppm Sr, Cs. They were then stirred and run through MP-AES for cations Ca^+ , Mg^+ , K^+ and Na^+ . Total CEC was calculated from these results.

3.1.2.6 Acid-oxalate Extractable Aluminium and Iron

Acid-oxalate extractable Al and Fe oxides (sesquioxides) were analysed following Blakemore et al.'s (1987) methodology. Here 0.4 g of soil was weighed into 50 mL Oak Ridge centrifuge tubes and 40 mL of acid-oxalate reagent (pH 3 ± 0.05) added. Samples were then loaded into an end-over-end shaker under dark for four hours before being centrifuged for 10 minutes at 11,872 g. Following this, samples were filtered through Whatman 42 filter paper and stored at $<4^\circ\text{C}$. Prior to analysis, 1 mL of supernatant was diluted at a rate of 1:10 with 9 mL of 2% HNO_3 before samples were run through MP-AES for Al and Fe.

3.2 Results and Discussion

3.2.1 Pukekawa

The Pukekawa site soil characterisation results are detailed below in Table 7, along with results from the other study farms. Full data sets for all soils can be seen in Appendix B. This site has the highest mean total soil Cd concentration across all sites of 0.52 mg kg^{-1} . This concentration is almost double NZ's mean total soil Cd concentration for cropping sites of 0.28 mg kg^{-1} (Cavanagh, 2014). However, this value puts this soil within Tier 0 of the TFMS ($0\text{-}0.6 \text{ mg Cd kg soil}^{-1}$), indicating that five-yearly soil tests for Cd are required however no fertiliser restrictions or other management actions are necessary. As this site also has a high total P content of 0.16% (NZ's general soil P range is 0.02-0.15% (McLaren & Cameron, 1996)), this is reflective of the area's past land-use and the large quantities of Cd-containing phosphate fertilisers which have been applied to this soil over time. This corresponds with the knowledge that P fertiliser application is the key factor influencing Cd soil accumulation, especially in intensively farmed agricultural areas (Loganathan et al., 2003). However, despite this area's high total Cd content, the

exchangeable Cd content of this soil is very low – a mean of 0.01 mg kg⁻¹ over 30 plots. Consequently, plant uptake of Cd from this soil is expected to be low, with little risk present here for food chain transfer (Al Mamun et al., 2016a).

This soil has a total Zn concentration of 196.90 mg kg⁻¹. This is similar to the total Zn concentration reported by Al Mamun et al. (2016a), of 173 mg kg⁻¹ for soil from this region. Land Resource Information System's (2016) 95th percentile estimate of total Zn for NZ soils is 97.97 mg kg⁻¹ – this soil contains more than double this concentration, giving it a very high Zn concentration relative to NZ soils. However, this does not constitute soil contamination by NZ standards, which entails Zn concentrations of >300 mg kg⁻¹ (New Zealand Water & Wastes Association, 2003). Like Cd, exchangeable Zn at this site is very low (0.02 mg kg⁻¹), indicating that little Zn is available for plant uptake.

This site has a relatively high mean soil pH of 6.27, the highest of all the study farms. The mean OM content of this soil is 5.53%, which sits at the lower end of NZ's mineral soil OM content range of 3-20% (McLaren & Cameron, 1996). It is possible this relatively low OM level is attributed to the well-drained status of this soil, which acts to prevent water-logged and anaerobic conditions and encourages the decomposition of OM (Landcare Research, 2016; McLaren & Cameron, 1996). The mean CEC of this site (17.27 meq 100g⁻¹) sits in the middle of NZ's typical soil CEC range of 5-30 meq 100g⁻¹ (McLaren & Cameron, 1996). This may explain the low concentrations of exchangeable Cd and Zn in this soil, as plentiful exchange sites exist with which Cd²⁺ and Zn²⁺ can bind, keeping them in the solid phase of the soil rather than as available ions in soil solution (McLaren & Cameron, 1996).

Mean acid-oxalate extractable Al and Fe oxides constitute 0.78% and 0.37% respectively. As Cavanagh et al. (2015) suggest that low Cd plant uptake in soils from the Pukekohe area can be attributed to high levels of Al and Fe oxides in these soils, this soil parameter may further explain the low exchangeable Cd concentrations at this site. This exemplifies the way in which soil type can affect Cd bioavailability in NZ soils.

The Pukekawa soil contains a mean total N content of 0.27%. This sits within the total N range for NZ topsoils of 0.1-0.6% (McLaren & Cameron, 1996). This N content is likely a result of past N fertiliser application, as this site constitutes a commercial horticulture plot with a history of production and fertiliser use.

Table 7. Mean soil characteristics of the study farms at Pukekawa, Manawatu and Lincoln

Soil Characteristic	Pukekawa ²	Manawatu ²	Lincoln Potato ²	Lincoln Wheat ²
Total Cd (mg kg ⁻¹)	0.52±0.06	0.26±0.04	0.13±0.01	0.13±0.02
Exchangeable Cd (mg kg ⁻¹)	0.01±0.004	0.02±0.019	0.02±0.005	0.02±0.003
pH	6.27±0.13	5.41±0.13	5.40±0.09	4.93±0.09
OM content (%)	5.53±0.15	4.06±0.23	4.70±0.11	4.29±0.26
CEC (meq 100g ⁻¹)	17.27±1.83	13.69±1.77	14.63±2.11	14.31±1.63
Total Zn (mg kg ⁻¹)	196.90±10.23	41.81±8.10	58.92±4.22	105.12±13.83
Exchangeable Zn (mg kg ⁻¹)	0.02±0.04	-	-	6.85±0.87
Acid-oxalate extractable Al content (%)	0.78±0.05	0.22±0.01	0.38±0.04	0.20±0.01
Acid-oxalate extractable Fe content (%)	0.37±0.03	0.24±0.04	0.22±0.03	0.25±0.03
Total P (%)	0.16±0.016	0.04±0.004	0.04±0.006	0.03±0.005
Total N (%)	0.27±0.01	0.22±0.01	0.22±0.01	0.21±0.01

²n=30, except Manawatu total Zn n=28 (Total Zn concentrations were below detection for two plots (7 and 8) at this site); Manawatu and Lincoln Potato exchangeable Zn n=0 (Exchangeable Zn concentrations at these sites were below detection); Lincoln Potato total Cd n=10 (Total Cd analysis for this soil was conducted externally by Hill Laboratories and only 10 samples were analysed); Lincoln Wheat CEC n=13 (No CEC data is available for plots 4-20 due to the high pH of these samples, which surpassed that of the blank during the pH measurement stage of the procedure).

3.2.2 Manawatu

The mean total Cd concentration for this site was 0.26 mg kg^{-1} , fitting this soil within Tier 0 of the TFMS. This total Cd concentration is characteristic of NZ cropping sites, which average 0.28 mg kg^{-1} (Cavanagh, 2014). Like the Pukekawa soil, this soil's mean exchangeable Cd concentration is low (0.02 mg kg^{-1}), indicating that there is little risk of Cd plant uptake and food chain transfer in this location. This site has a relatively low mean total P content of 0.04%, indicating that this soil may not have historically received intensive P fertiliser inputs, contributing to its low total Cd concentration.

This site has acidic soil with a mean pH of 5.41. The mean OM content of this soil is low (4.06%) in comparison to NZ standards, with a relatively low mean CEC of $13.70 \text{ meq } 100\text{g}^{-1}$. Thus, compost additions here may improve both OM content and CEC. As this soil is poorly drained, compost amendments may undergo slow decomposition thus maintaining a high OM content in the soil for an extended period post-amendment application (Landcare Research, 2016; McLaren & Cameron, 1996).

The mean total Zn concentration of this soil was the lowest of all sites, at 41.81 mg kg^{-1} . Mean acid-oxalate extractable Al and Fe oxide contents of this site were 0.22% and 0.24% respectively. The Manawatu soil (Kairanga silty clay) is a result of moderate weathering of quartzo-feldspathic sediment (NZ Soils, n.d.). The relatively low quantities of Al and Fe oxides in this soil are as expected due to the lack of weathering and absence of ferromagnesian minerals in the soil's parent material (McLaren & Cameron, 1996).

Mean total N content of the Manawatu soil constitutes 0.22%. As with the Pukekawa soil, this is likely reflective of past N fertiliser inputs due to the site's location on a horticultural production area.

3.2.3 Lincoln Potato

The mean total Cd concentration of this soil was 0.13 mg kg^{-1} , placing this soil within Tier 0 of the TFMS. This soil contains a lower total Cd concentration than the NZ average for cropping sites of 0.28 mg kg^{-1} . Like other sites, mean exchangeable Cd was very low at this site (0.02 mg kg^{-1}) indicating that little bioavailable Cd (and thus risk of exceeding international food standards) presently exists in this soil. The mean total P content of 0.04% is a low value for NZ soils, and indicates that, like the Manawatu site, there is likely an absence of past intensive Cd-containing phosphate fertiliser inputs at this site.

This site's mean soil pH of 5.40 shows the soil to be acidic. The mean OM content and CEC of this soil are also low within the range for NZ soils, at 4.70% and 14.60 meq 100g⁻¹ respectively. This may be attributed to the well-drained status of this soil, which prevents waterlogged conditions and promotes the decomposition of OM (Landcare Research, 2016). Again, compost amendments may be beneficial at this location to increase both OM content and CEC of the soil for the purposes of increased Cd adsorption and complexation (Roberts, 2014).

The mean total Zn concentration of this soil is 58.92 mg kg⁻¹. This falls below Land Resource Information System's (2016) 95th percentile estimate of 97.97 mg kg⁻¹ for NZ, however falls within the range of total soil Zn concentrations for Canterbury and Southland of 38.1-113.8 mg kg⁻¹ soil detailed by Chowdhury (1990).

The Al and Fe oxide contents of this soil are 0.38% and 0.22% respectively. This gives this site the lowest Fe oxide content across all four sites. This is attributed to the young age of this immature soil, as Al and Fe oxides exist in the highest quantities in highly weathered soils which are likely to form over greater time-periods (McLaren & Cameron, 1996). Furthermore, this soil is formed from finely textured post-glacial alluvium which contains little ferromagnesian material necessary for the formation of Fe oxides in soil (McLaren & Cameron, 1996; NZ Soils, n.d.). Total N for this soil is 0.22%, the same as the Manawatu soil and at the lower range of NZ's soil N content of 0.1-0.6% (McLaren & Cameron, 1996).

3.2.4 Lincoln Wheat

This site contains a low mean total Cd concentration of 0.13 mg kg⁻¹, putting this soil (like the other sites) in Tier 0 of the TFMS. This soil sits below the NZ mean for cropping sites of 0.28 mg kg⁻¹. As with the other three soils, mean exchangeable Cd at the Lincoln Potato site is very low (0.02 mg kg⁻¹) indicating that there is little risk of plant uptake and food chain transfer. Total P content for this soil is 0.03%, which is a low value relative to NZ's general soil range of 0.02-0.15% (McLaren & Cameron, 1996). This indicates a lack of historical intensive P fertiliser use at this site, and the low total Cd concentration of this soil is attributed to this.

This soil had the lowest pH of all soils, with a mean value of 4.93. Thus this site will require greater quantities of lime to bring its pH into a range more appropriate for potato cultivation and Cd adsorption (Hill Laboratories, 2002). The mean OM content for this soil (4.29%) is low relative to NZ's range of 3-20%. This soil's mean CEC is 14.70 meq 100g⁻¹. Both the OM content and CEC are comparable to that of the Lincoln Potato soil, which is attributed to the close proximity of these sites and their well-drained status which promotes OM decomposition (Landcare Research, 2016). It therefore follows that, like the Lincoln Potato soil, this soil is likely to benefit from compost amendments in terms of increased OM content and the resultant decrease

in Cd bioavailability, as a result of increased Cd adsorption and complexation by OM (Roberts, 2014).

The mean total Zn concentration at this site (105.12 mg kg⁻¹) exceeds the 95th percentile value for NZ, giving this soil a high total Zn concentration relative to NZ soils (Land Resource Information System, 2016). This is further illustrated when the mean Zn concentration is compared to the range presented by Chowdhury (1990) for Canterbury and Southland soils of 38.1-113.8 mg kg⁻¹. However, this is not representative of Zn soil contamination in NZ, which occurs at concentrations >300 mg kg⁻¹ (New Zealand Water & Wastes Association, 2003). The mean exchangeable Zn content of this soil is 6.85 mg kg⁻¹.

Al and Fe oxides measure a mean of 0.20% and 0.25% respectively, giving this soil the lowest Al oxide content across all four sites. Like the Lincoln Potato soil, this is attributed to the immature nature of this soil (McLaren & Cameron, 1996). Total N content averages 0.21% at the Lincoln Wheat site, the lowest of all four soils, however within NZ's general soil N range of 0.1-0.6% (McLaren & Cameron, 1996).

Many of this soil's characteristics are comparable to that of the Lincoln Potato soil, which is expected due to the close proximity of the two sites. In particular, total and exchangeable Cd, Fe oxides, total P and total N are comparable between these sites. As total Cd, P and N content are reflective of fertiliser use history, this is congruent with the expectation that both sites have undergone a similar land-use history including fertiliser application.

4 Research to Derive Accurate Application Rates to Achieve Target pH Values in Soil

As soil pH is a key driver of the mobility of Cd in NZ soils, its management is crucial for healthy horticultural systems. Soil pH also affects crop cultivation, as crops have an ideal soil pH range in which they thrive (Hill Laboratories, 2002). As part of the field trial project, lime and S amendments were applied to potato (Pukekawa, Manawatu and Lincoln) and wheat (Lincoln) plots with the aim of producing a range of target pH values. These pH values would then be assessed to determine which soil pH resulted in the greatest amount of Cd fixation in the soil's solid phase while also having minimal effects on plant yield and quality. The generation of target pH values in a field situation is challenging due to the soil's pH buffering capacity which resists pH changes, and makes the calculation of required amendment rates a complex task (Rogovska & Blackmer, n.d.).

4.1 Materials and Methods

4.1.1 Soils

In order to determine the most suitable lime and acid form and application rates to meet the field trial pH targets at each field site (5.6, 6, 6.3, 6.7 and 7), pH incubation experiments were conducted on each soil. A composite transect sample consisting of 15 (15 cm x 2.5 cm) soil cores was collected at each site. The soil was air dried at 35-40°C and sieved to 2 mm prior to the experiments.

4.1.2 Lime and Sulphur

Two types of lime were used in the pH incubation experiments to determine the most appropriate type and application rate in order to ascertain a desired pH range. Aglime (CaCO₃ 80%) and hydrated lime (Ca(OH)₂ 90%) were sourced from Farmlands in Palmerston North. Elemental S (S 100%) was used as the acid addition in the incubation experiments.

4.1.3 Soil Buffering Capacity

A pH buffer curve was created to determine each soil's buffer capacity. To do this, 20 g of soil from each site was weighed into 10 120 mL plastic beakers. The volumes of 0.2 M NaOH and 0.2 M HCl detailed in Table 8 were then added. The soil was stirred and left to incubate for 25 minutes before 42 mL of deionised water was added to each beaker to bring the total volume to

50 mL with a 1:2.5 soil:solution ratio. The soil suspension was then stirred and left for at least five minutes. The pH was then recorded using a pH electrode. This data was inserted into Microsoft Excel to generate a buffer curve and thus calculate the soil's buffer capacity using the equation of the buffer curve (see Appendix C). The required quantities of aglime (CaCO_3 80%), hydrated lime ($\text{Ca}(\text{OH})_2$ 90%) and elemental S (S 100%) to ascertain a targeted pH range (5.6, 6, 6.3, 6.7, and 7) were calculated in Excel. These calculations are detailed in Appendix C.

Table 8. Volumes of 0.2 M NaOH, 0.2 M HCl and deionised H_2O added to beakers containing 20 g of soil to create a pH buffer curve for each soil

Beaker No.	Volume added (mL)			Amounts of H^+/OH^- added (mmol kg soil^{-1})	
	DI H_2O	0.2 M NaOH	0.2 M HCl	OH^-	H^+
1	2	6	-	60	-
2	3	5	-	50	-
3	4	4	-	40	-
4	5	3	-	30	-
5	6	2	-	20	-
6	8	-	-	-	-
7	7	-	1	-	10
8	6	-	2	-	20
9	4	-	4	-	40
10	2	-	6	-	60

4.1.4 Amendment Rate Determination

Once required amendment rates had been determined from each soil's pH buffer curve, previous work was drawn on to decide the final amendment rates of each material for pH incubations: Stafford (2016) completed work in which required amounts of aglime and elemental S to effect a 0.1 unit pH change had been calculated from a pH buffer curve (x) and measured in field (y), before being compared to find the relationship between the two (y/x). This gave a figure which the pH buffer curve results could then be multiplied by to determine the amount needed in-field to create the desired pH change. This was necessary as buffer curve-generated rates tend to be lower than actual rates needed in-field to achieve a target pH (Ketterings et al., 2010).

The pH incubation experiments drew on Stafford's (2016) work and results, using values of 10 and 20 for liming materials (by which the required amounts of lime for each pH unit shift calculated from the pH buffer curve were multiplied by 10 and 20 to determine the incubation amendment rates), and a value of three for elemental S. The efficacy of these rates was then tested in pH incubation experiments, with a single rate and amendment form decided upon for use in field trials.

4.1.5 pH Incubations

Once amendment rates had been determined, pH incubations were set up with 20 g of Pukekawa, Lincoln Potato and Lincoln Wheat soil and 40 g of Manawatu soil (due to the availability of each soil) put into 75 mm x 100 mm plastic zip lock bags. One bag was used per treatment, per soil. Required amendments of aglime, hydrated lime and elemental S were added homogeneously by hand to each bag by spreading soils evenly into four trays (~5 g per tray) and mixing in the amendments in four even parts, before combining the sample back together in the ziplock bag. Deionised water was added to 70% field capacity, and this was maintained throughout the incubation. Each soil's bulk density and field capacity is detailed in Table 9. Two small holes (6 mm diameter) were punched in through each bag (four holes total) using a soil corer to ensure aerobic conditions were present within the soils throughout the incubation. Incubations were then stored in an incubator between 22-24°C, with pH measurements taken at seven and 10 days. This data was used to ascertain the most efficient form of lime amendment for generating a target pH for use in field trials, and the required application rates of each amendment in order to reach a target pH.

The samples were then left to incubate for a further 274 (Pukekawa, Lincoln Wheat and Lincoln Potato) and 231 (Manawatu) days with pH measurements taken at days 101 and 274 (Pukekawa, Lincoln Wheat and Lincoln Potato) and 58, 121 and 231 (Manawatu). This data was then compared to field data where equivalent amendments had been applied in order to assess the variance between laboratory and field situations.

Table 9. Bulk density and field capacity of each soil. Pukekawa soil information sourced from Stevenson (2008) and Watson (1965); Manawatu soil information sourced from Wheeler (2015) and Sparling, Wheeler, Vesely, and Schipper (2006); Lincoln soil information sourced from Landcare Research (2015).

Soil	Bulk Density (g cm ³ ⁻¹)	Field Capacity (%)
Pukekawa	1.14	41
Manawatu	0.97	37
Lincoln Potato	1.22	32
Lincoln Wheat	1.22	32

4.2 Results & Discussion

4.2.1 Soil Buffering Capacity

pH buffer curves were generated for each soil, for use in calculating the soil's buffer capacity. In each case, the section of the pH buffer curve which contained the targeted pH range (5.6-7.0) was isolated and a trendline applied. These buffer curves and their equations can be seen Figure 4. The equation of each trendline was then used to calculate the soil's buffer capacity for each required pH unit shift from native soil pH to target pH. The buffering capacity for the relevant soil pH range and native pH for each site are detailed in Table 10. Full details and calculations

can be found in Appendix C. The pH range-specific buffering capacity of the Lincoln Potato and Lincoln Wheat soils was comparable (10.52 and 10.55 mol OH⁻/H⁺ kg soil⁻¹pH unit⁻¹ respectively), which is attributed to their close proximity and common soil type. The Pukekawa and Manawatu soils had higher pH range-specific buffering capacities of 12.15 and 13.18 mol OH⁻/H⁺ kg soil⁻¹ pH unit⁻¹ respectively.

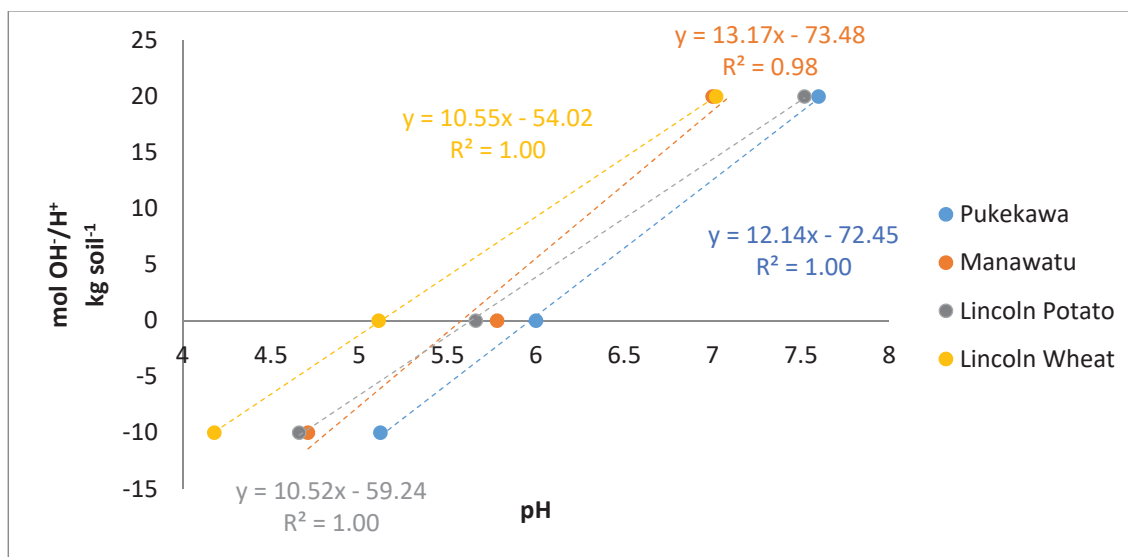


Figure 4. Buffer curves of all soils inclusive of target pH range. Note, positive values on the y-axis indicate mol OH⁻ while negative values indicate mol H⁺ kg soil⁻¹.

Table 10. Native pH and buffering capacities of incubated soils

Soil	Native pH	Buffering Capacity of Relevant pH Range (mol OH ⁻ /H ⁺ kg soil ⁻¹ pH unit ⁻¹)
Pukekawa	6.00	12.15
Manawatu	5.78	13.18
Lincoln Potato	5.66	10.52
Lincoln Wheat	5.11	10.55

4.2.2 Amendment Rates for use in pH Incubations

Accurately achieving a target pH was a key aim of this study. In the current work, several liming products and several application rates, derived from each soil's buffer curve and adjusted based on the work of Stafford (2016) were tested (section 4.1.4). Required amendment rates for a series of pH targets at each site which were tested in pH incubation experiments are detailed in Table 11. The Pukekawa soil had 14 differing treatments, while the Manawatu had 18, Lincoln Potato 18 and Lincoln Wheat 21. A rate of both aglime and hydrated lime at 10 times and 20 times that generated by the pH buffer curve was used for each pH target above the control. Elemental S at a rate of three times that generated by the pH buffer curve was tested for its efficiency in achieving

pH targets below the control. No acid addition was tested for the Lincoln Wheat soil, as it contained an already-low pH of 5.11.

Of the four liming products and amendment rates, one was picked which most effectively and consistently obtained the target pH after 10 days of incubation. This amendment and rate were recommended for use in field trial work, to be applied in-field at each site to achieve a series of pH targets.

Table 11. pH incubation amendments and rates for each site, derived from pH buffer curve data to achieve a range of target pH values

	Treatment	Amendment	Target pH	t ha ⁻¹ of amendment for target pH	g amendment soil sample ⁻¹
Pukekawa	1	Elemental S*3	5.60	0.40	0.005
	2	(control)	6.00	-	-
	3	Aglime*10	6.30	3.90	0.046
	4	Aglime*20	6.30	7.80	0.091
	5	Aglime*10	6.70	9.10	0.106
	6	Aglime*20	6.70	18.20	0.213
	7	Aglime*10	7.00	13.00	0.152
	8	Aglime*20	7.00	26.01	0.304
	9	Hydrated lime *10	6.30	2.57	0.030
	10	Hydrated lime *20	6.30	5.13	0.060
	11	Hydrated lime *10	6.70	5.99	0.070
	12	Hydrated lime *20	6.70	11.97	0.140
	13	Hydrated lime *10	7.00	8.55	0.100
	14	Hydrated lime *20	7.00	17.11	0.200
Manawatu	1	Elemental S*3	5.60	0.17	0.005
	2	(control)	5.78	-	0.000
	3	Aglime*10	6.00	2.65	0.072
	4	Aglime*20	6.00	5.29	0.145
	5	Aglime*10	6.30	6.26	0.171
	6	Aglime*20	6.30	12.51	0.343
	7	Aglime*10	6.70	11.07	0.303
	8	Aglime*20	6.70	22.14	0.606
	9	Aglime*10	7.00	14.68	0.402
	10	Aglime*20	7.00	29.36	0.804
	11	Hydrated lime *10	6.00	1.74	0.048
	12	Hydrated lime *20	6.00	3.48	0.095
	13	Hydrated lime *10	6.30	4.12	0.113

	14	Hydrated lime *20	6.30	8.23	0.225
	15	Hydrated lime *10	6.70	7.28	0.199
	16	Hydrated lime *20	6.70	14.56	0.399
	17	Hydrated lime *10	7.00	9.66	0.264
	18	Hydrated lime *20	7.00	19.31	0.529
Lincoln Potato	1	Elemental S*3	5.60	0.06	0.001
	2	(control)	5.66	-	-
	3	Aglime*10	6.00	4.09	0.048
	4	Aglime*20	6.00	8.18	0.096
	5	Aglime*10	6.30	7.70	0.090
	6	Aglime*20	6.30	15.41	0.180
	7	Aglime*10	6.70	12.52	0.146
	8	Aglime*20	6.70	25.03	0.292
	9	Aglime*10	7.00	16.13	0.188
	10	Aglime*20	7.00	32.26	0.377
	11	Hydrated lime *10	6.00	2.69	0.031
	12	Hydrated lime *20	6.00	5.38	0.063
	13	Hydrated lime *10	6.30	5.07	0.059
	14	Hydrated lime *20	6.30	10.13	0.118
	15	Hydrated lime *10	6.70	8.23	0.096
	16	Hydrated lime *20	6.70	16.47	0.192
	17	Hydrated lime *10	7.00	10.61	0.124
	18	Hydrated lime *20	7.00	21.22	0.248
Lincoln Wheat	1	(control)	5.11	-	-
	2	Aglime*10	5.60	5.91	0.069
	3	Aglime*20	5.60	11.82	0.138
	4	Aglime*10	6.00	10.74	0.125
	5	Aglime*20	6.00	21.48	0.251
	6	Aglime*10	6.30	14.39	0.168
	7	Aglime*20	6.30	28.72	0.335
	8	Aglime*10	6.70	19.19	0.224
	9	Aglime*20	6.70	38.37	0.448
	10	Aglime*10	7.00	22.81	0.266
	11	Aglime*20	7.00	45.61	0.533

12	Hydrated lime *10	5.60	3.89	0.045
13	Hydrated lime *20	5.60	7.78	0.091
14	Hydrated lime *10	6.00	7.06	0.082
15	Hydrated lime *20	6.00	14.13	0.165
16	Hydrated lime *10	6.30	9.44	0.110
17	Hydrated lime *20	6.30	18.89	0.221
18	Hydrated lime *10	6.70	12.62	0.147
19	Hydrated lime *20	6.70	25.24	0.295
20	Hydrated lime*10	7.00	15.00	0.175
21	Hydrated lime*20	7.00	30.00	0.350

¹Soil sample size was 20 g for Pukekawa, Lincoln Potato & Lincoln Wheat soils, and 40 g for the Manawatu soil

4.2.3 pH Incubation Results

The results of the pH incubations at days seven & 10 using aglime, hydrated lime and elemental S are plotted below in Figures 5-12. Aglime applied at a rate of 10 times that generated by the pH buffer curve (aglime*10) proved the most efficient liming material for obtaining the desired pH target for all soils after both seven and 10 days of incubation and was thus recommended as the appropriate lime amendment for use in field trials. This is observable in Figures 5 and 6, in which the incubated Pukekawa soil pH is plotted at day seven and day 10 respectively. Of the four liming amendments tested (aglime*10, aglime*20, hydrated lime*10 and hydrated lime*20), the observed pH of aglime*10 appears closest to the target pH (illustrated by the x=y trendline) at both timepoints. Aglime*20, hydrated lime*10 and hydrated lime*20 produced a pH higher than both the target and aglime*10, indicating that these rates of application were too high for the desired target values. This was the case for all soils at both days seven and 10. Elemental S applied at a rate of three times that generated by the pH buffer curve (Elemental S*3) produced a pH close to the target pH in all soils, however was less effective in the Pukekawa soil producing a pH slightly above target (5.95 and 5.89 at seven and 10 days respectively for a target of 5.6). From this, elemental S*3 was recommended as the acid addition to lower soil pH in field trial work.

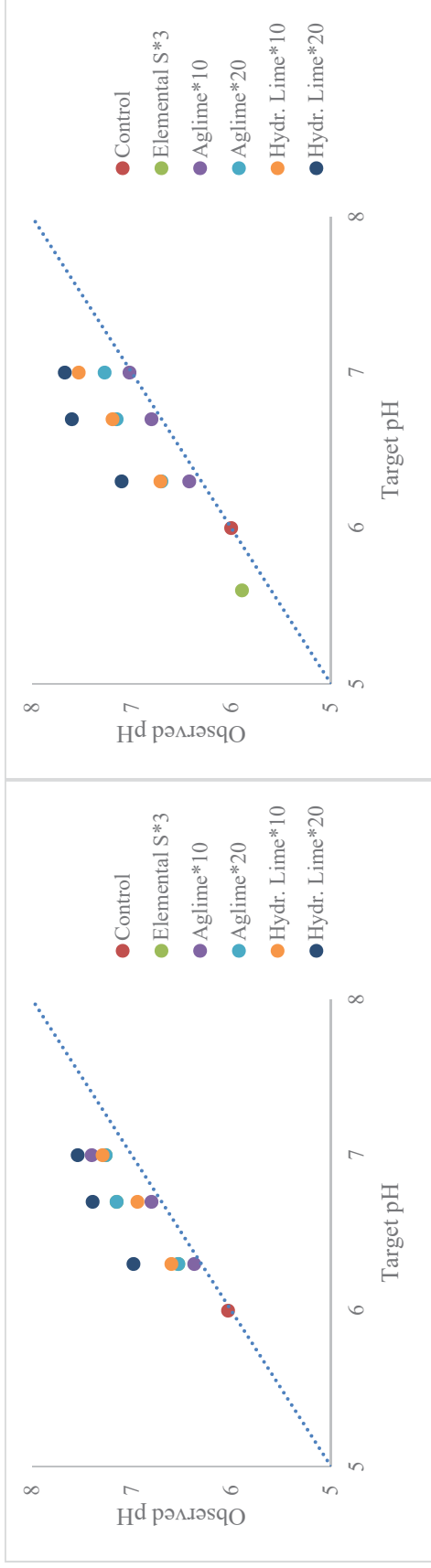


Figure 5 (left). Pukekawa soil pH after seven days of incubation with aglime, hydrated lime and elemental S amendments
 Figure 6 (right). Pukekawa soil pH after 10 days of incubation with aglime, hydrated lime and elemental S amendments

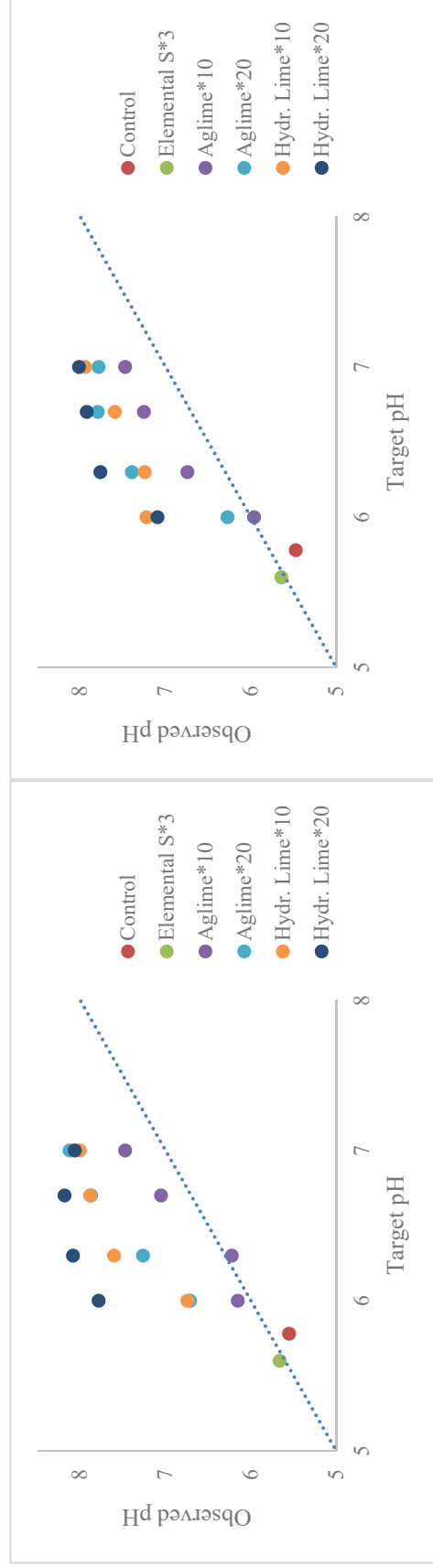


Figure 7 (left). Manawatu soil pH after seven days of incubation with aglime, hydrated lime and elemental S amendments
 Figure 8 (right). Manawatu soil pH after 10 days of incubation with aglime, hydrated lime and elemental S amendments

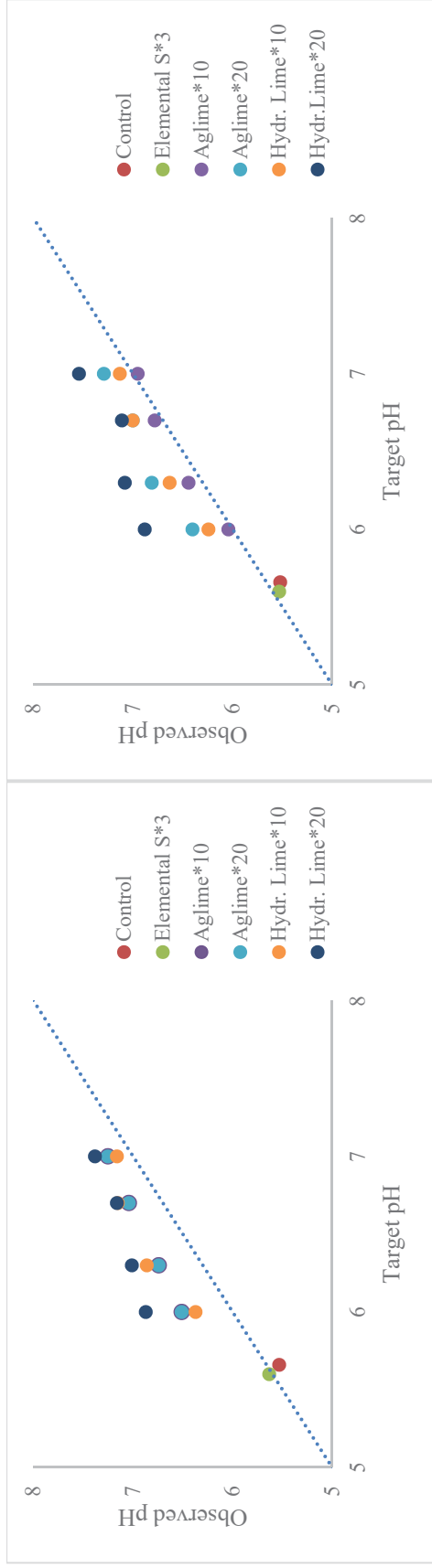


Figure 9 (left). Lincoln Potato soil pH after seven days of incubation with aglime, hydrated lime and elemental S amendments

Figure 10 (right). Lincoln Potato soil pH after 10 days of incubation with aglime, hydrated lime and elemental S amendments

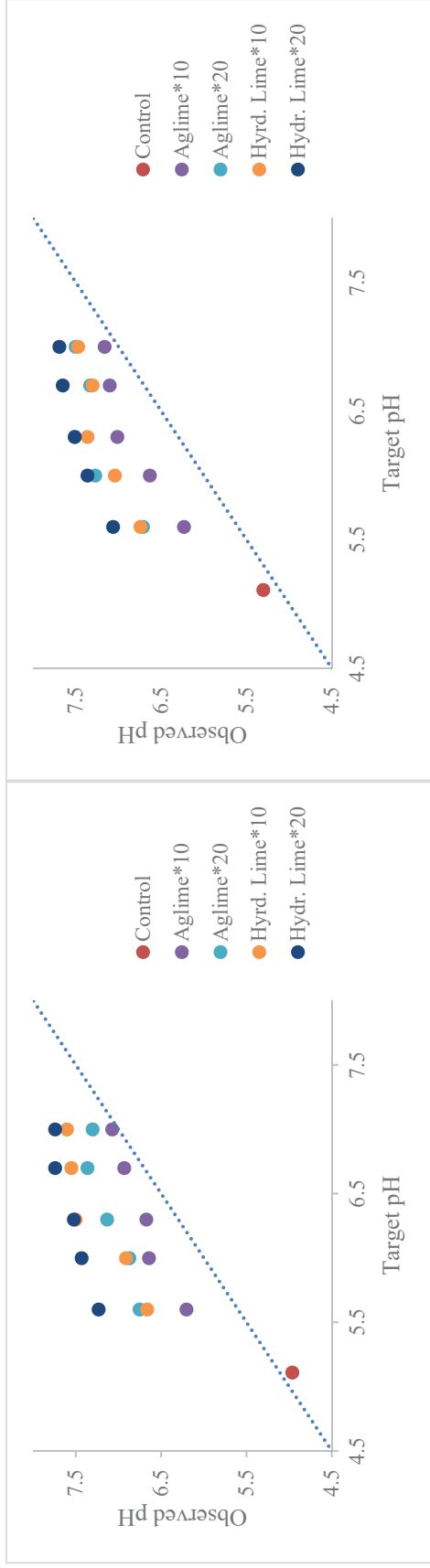


Figure 11 (left). Lincoln Wheat soil pH after seven days of incubation with aglime, hydrated lime and elemental S amendments

Figure 4 (right). Lincoln Wheat soil pH after 10 days of incubation with aglime, hydrated lime and elemental S amendments

4.2.4 Calculation of Field Trial Amendment Rates

Following the pH incubation work, in-field application rates were calculated per plot for each site, using the aglime*10 and elemental S*3 amendment rates shown in Table 11. These per plot application rates are detailed in Table 12. Potato plots measured 4 m by 3.4 m, while wheat plots measured 1.65 m by 3 m. These rates were recommended as a result of this work for use in field trials to generate the desired range of pH target values at each site.

Table 12. Amendment rates of elemental S or aglime per plot used in field trial work in four experimental locations

Site	Amendment and Factor	Target pH	Observed pH at Incubation Day 10	t amendment ha ⁻¹ for target pH	kg amendment plot ⁻¹
Pukekawa	Elemental S*3	5.60	5.98	0.40	0.54
	(control)	6.00	6.03	-	0.00
	Aglime*10	6.30	6.42	3.90	5.31
	Aglime*10	6.70	6.80	9.10	12.38
	Aglime*10	7.00	7.02	13.00	17.68
Manawatu	Elemental S*3	5.60	5.64	0.17	0.23
	(control)	5.78	5.47	-	0.00
	Aglime*10	6.00	5.96	2.65	3.60
	Aglime*10	6.30	6.42	6.26	8.51
	Aglime*10	6.70	6.80	11.07	15.06
Lincoln Potato	Elemental S*3	5.60	5.53	0.06	0.08
	(control)	5.66	5.52	-	0.00
	Aglime*10	6.00	6.04	4.09	5.57
	Aglime*10	6.30	6.44	7.70	10.48
	Aglime*10	6.70	6.78	12.52	17.02
Lincoln Wheat	Elemental S*3	5.60	5.53	0.06	0.08
	(control)	5.11	5.30	-	0.00
	Aglime*10	5.60	6.23	5.91	2.93
	Aglime*10	6.00	6.63	10.74	5.32
	Aglime*10	6.30	7.01	14.39	7.12
Lincoln Wheat	(control)	5.11	5.30	-	0.00
	Aglime*10	5.60	6.23	5.91	2.93
	Aglime*10	6.00	6.63	10.74	5.32
	Aglime*10	6.30	7.01	14.39	7.12
	Aglime*10	6.70	7.10	19.19	9.50
Lincoln Wheat	Aglime*10	7.00	7.16	22.81	11.29

4.2.5 Extended pH Incubation Results

As the pH incubation samples were left to incubate for 274 (Pukekawa, Lincoln Potato and Lincoln Wheat) and 231 days (Manawatu), it was possible to assess the efficacy of amendments at maintaining the target pH values over time. Aglime*10 remained the most efficient liming amendment throughout incubations, until day 231 for Manawatu soil and day 274 for Pukekawa, Lincoln Potato and Lincoln Wheat soils, consistently producing a pH value closer to the target than any other liming amendment.

The incubated Manawatu soil samples with aglime*10 and elemental S*3 amendments had pH measurements taken at days 58, 131, and 231. These results are shown in Figures 13, 14, and 15. The elemental S*3 amendment here continues to effect increasing change on the soil's pH over time, taking it further below the target pH with each progressive pH measurement. The aglime*10 amended samples however become closer to the target pH by day 231, with the exception of pH target 6 sample which falls below the target to a pH value of 5.47. Thus, the lime amendments in this soil effect an initial sharp increase in pH, before reaching an equilibrium over an extended time-period which brings the soil pH closer to the target value.

This same trend is evident in the incubated Lincoln Potato soil, which had pH measurements taken at days 101 and 274. Figure 16 shows the incubation pH at day 101, where all limed samples had raised the soil pH to above the target value. By day 274 however (Figure 17), the pH of these samples had declined to bring them near to the target pH. Like the Manawatu soil, the Lincoln Potato soil incubated with elemental S continued to reduce in pH over time, illustrating the drawn out effect of this acid amendment at effecting pH changes on this soil.

Thus, over time the elemental S*3 amendment rate became less effective at producing the target pH of 5.6, as it continued to decrease the soil pH below target up to day 231 in the Manawatu soil and day 274 in the Lincoln Potato soil. The aglime*10 rate however increased in efficiency over time, with each time point showing pH values closer to their targets. This demonstrates the complicated nature of soil pH management, and illustrates how differing amendments interact with the soil and its buffering capacity in ways which produce varying results.

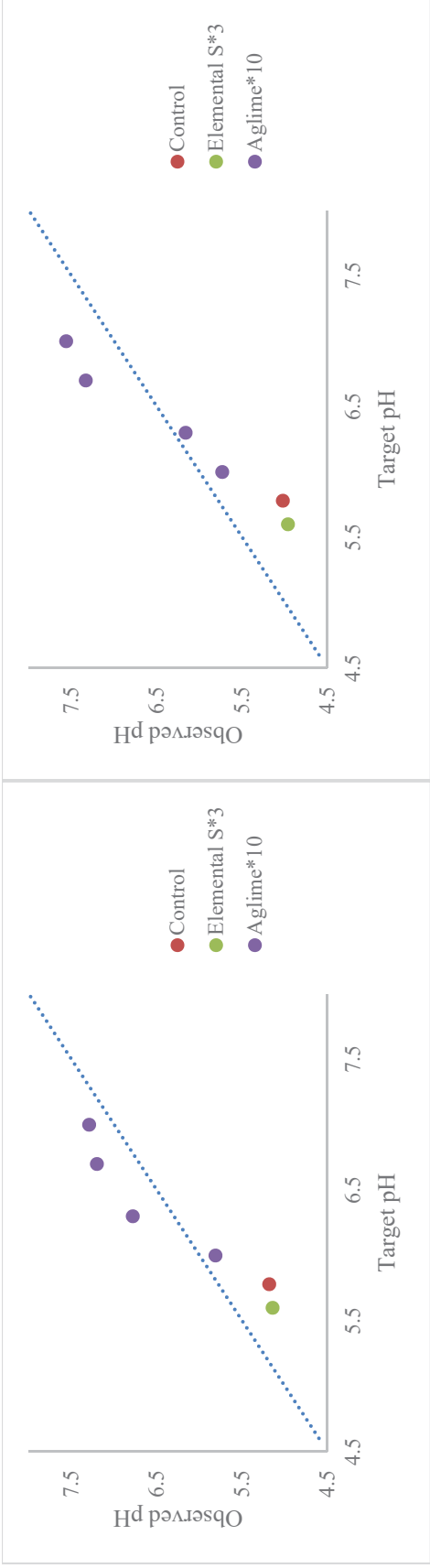


Figure 5 (left). Manawatu incubation pH at day 58 for aglime*10, elemental S*3 and control samples

Figure 6 (right). Manawatu incubation pH at day 121 for aglime*10, elemental S*3 and control samples

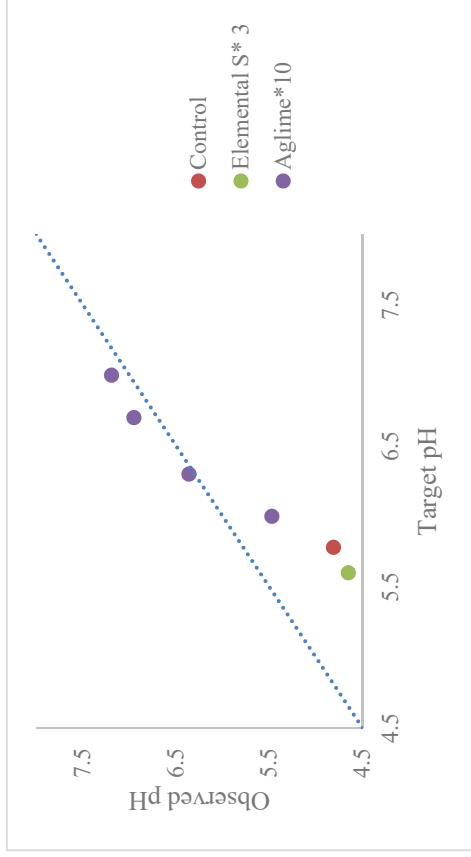


Figure 7. Manawatu incubation pH at day 231 for aglime*10, elemental S*3 and control samples

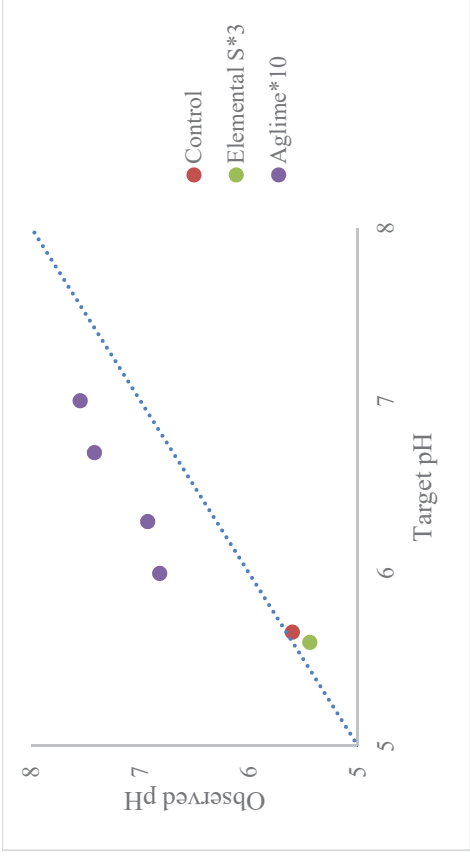


Figure 86. Lincoln Potato incubation pH at day 101 for aglime*10, elemental S*3 and control samples

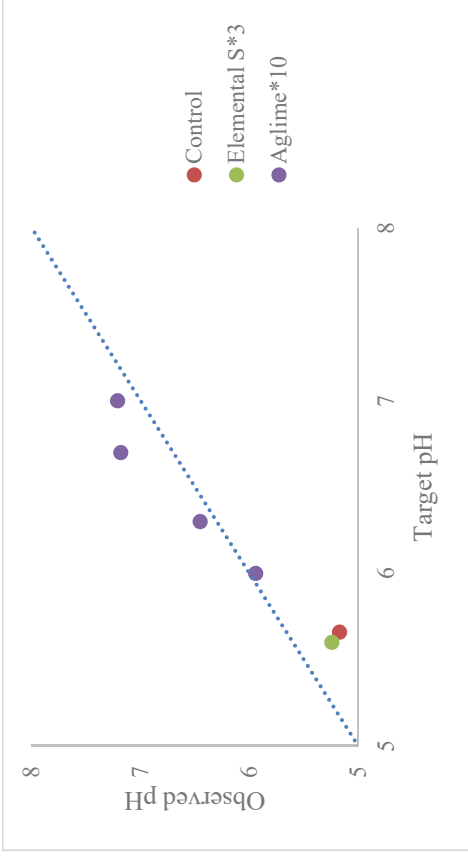


Figure 17. Lincoln Potato incubation pH at day 274 for aglime*10, elemental S*3 and control samples

4.2.6 pH: From Incubation to Field

The pH of Pukekawa and Lincoln Wheat incubations using aglime*10 and elemental S*3 were compared to field pH data where equivalent application rates of amendments had been applied in order to assess the difference between laboratory and field pH. The pH data from incubations of Pukekawa soil after 101 and 274 days are shown in Figures 18 and 19. The Pukekawa field site was sampled (in the same way as described in section 3.1.1) and the pH of each plot measured (as detailed in section 3.1.2.3) 147 days after amendments were applied to the soil. The average pH of control plots and those with lime only applications were measured and are plotted in Figure 20. The incubation at 101 days and the field situation at 147 days show comparable trends in the pH of lime samples/plots, although all generate a higher-than-target pH. This suggests that the lime has affected the soil pH to a comparable degree both in field and laboratory conditions. The elemental S however, produced a pH very close to the target of 5.6 (5.55) in the incubated sample, while in field produced a higher-than-target pH of 5.96. Thus, the acid addition was more effective at creating the desired pH change in laboratory conditions. A t-test using Minitab software showed no significant difference ($p=0.819$) between field and incubation pH values for both lime and acid amendments, supporting the conclusion that interaction of acid and lime with Pukekawa soil were comparable between the field situation and the incubation experiments.

The pH of incubated Lincoln Wheat soil amended with aglime*10 (as well as the control sample) was measured at 101 and 274 days, while the field pH of plots amended with equivalent amounts of lime was measured 139 and 169 days after amendment application. The results of these pH measurements are presented in Figures 21 and 22 (incubation pH) and Figures 23 and 24 (field pH). This site did not contain any acid additions to the soil as the native pH was very low (5.11). When the incubated soil at day 101 (Figure 21) and the field plots at day 139 (Figure 23) are compared, similar trends are observed between the plots. The same comparable trend in pH values exists between incubated soil at day 274 (Figure 22) and field plots at day 169 (Figure 24). Again, all pH measurements for this soil are above the target pH.

A t-test for this data revealed a significant difference ($p=0.035$) between the incubated soil at day 101 and the field situation at day 139, however no significant difference ($p=0.334$) between incubated soil at day 274 and the field situation at day 169. Thus despite the time differences between these incubation and field measurements, there is no significant difference between the soil pH. This suggests that over time an equilibrium is reached in the soil and the lime affects soil pH to a comparable degree between laboratory and field situations. Table 13 details the percentage variation of the

incubated soil pH at day 101 and the field pH at day 139 from the target pH. The incubations show greater variance (an average of 17.11% higher than the target pH) compared to the field situation (an average of 4.80% higher than the target pH). Both situations show similar trends in that the observed pH undergoes less variation from the target pH as the target pH increases, with the least variation observed for the target of 6.7. Thus it appears that lime amendments interact similarly with the Lincoln Wheat under laboratory and field conditions, with this similarity being more pronounced over time.

From this incubation and field data, it can be concluded that the amendments interacted with each soil in a non-uniform way, with amendments affecting different degrees of change in soil pH between sites over time. This is attributed to the differing pH buffering capacity of each soil, which impacts the soil’s ability to resist changes in pH.

This analysis is limited by the timing of field sampling. As this was subject to weather conditions and other practical considerations (including travel to field sites), it was not possible to sample the field trial locations on the same days that incubated samples were pH tested. Thus it is not possible to compare exact time points between incubations and field situations, and as such the closest time points between lab and field were compared. From this, general trends over time can be identified for both situations, and conclusions drawn. Due to the lack of significant difference between the incubation and field data at different time points (excluding the Lincoln Wheat soil at incubation day 101 and field day 139), the conclusion that lime interacts similarly with these soils in both incubation and field settings as the soil pH eventually reaches an equilibrium is supported.

Table 13. Percentage variations from target pH of Lincoln Wheat soil in incubations at day 101 and in field at day 139

Target pH	% variation from target pH in incubation at day 101	% variation from target pH in field at day 139
5.6	18.39	6.61
6.0	20.67	6.83
6.3	17.14	4.13
6.7	12.24	1.64

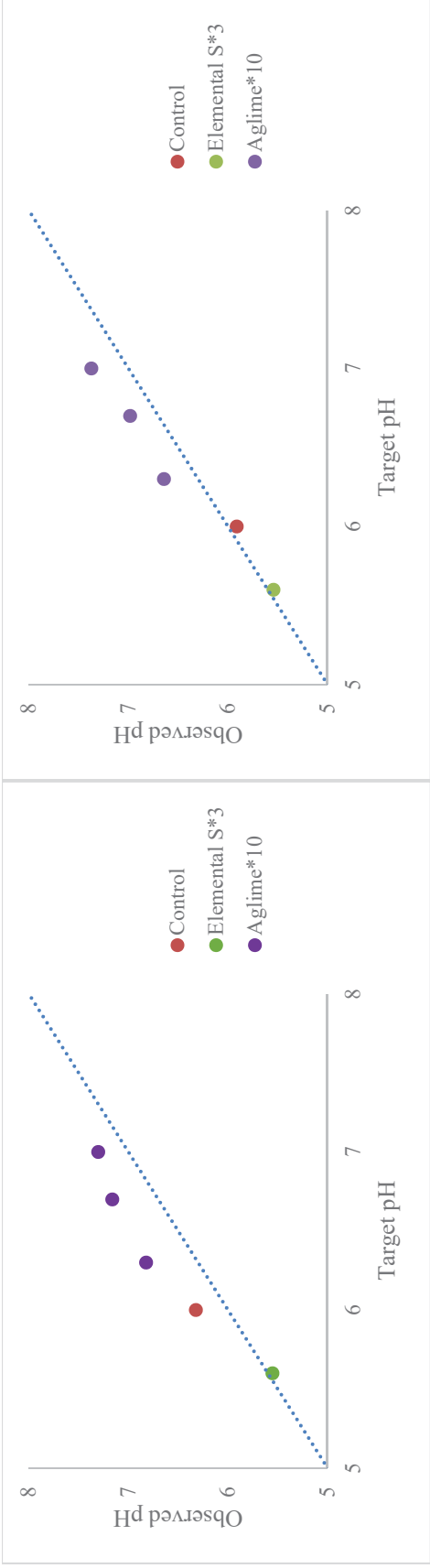


Figure 18 (left). Pukekawa soil incubation pH after 101 days

Figure 19 (right). Pukekawa soil incubation pH after and 274 days

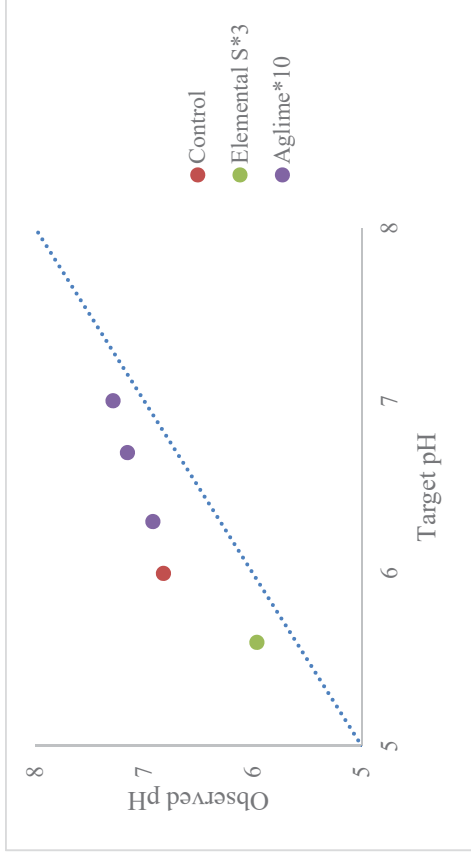


Figure 20. Pukekawa field pH of control, S and lime plots 147 days after amendment application

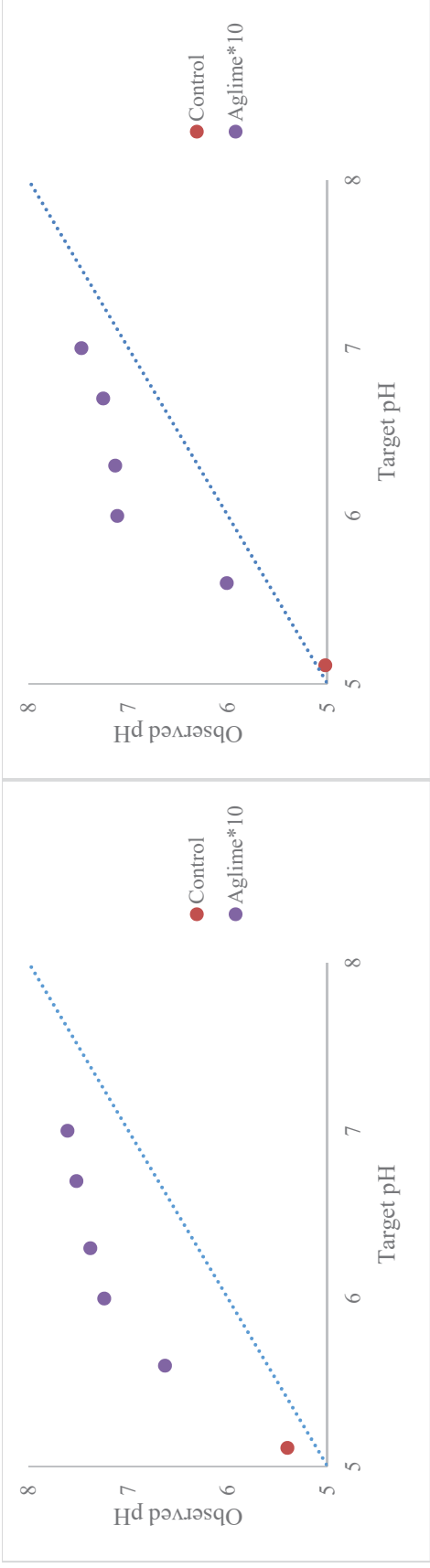


Figure 21 (left). Lincoln Wheat incubation pH of control and aglime*10 samples after 101 days

Figure 22 (right). Lincoln Wheat incubation pH of control and aglime*10 samples after 274 days

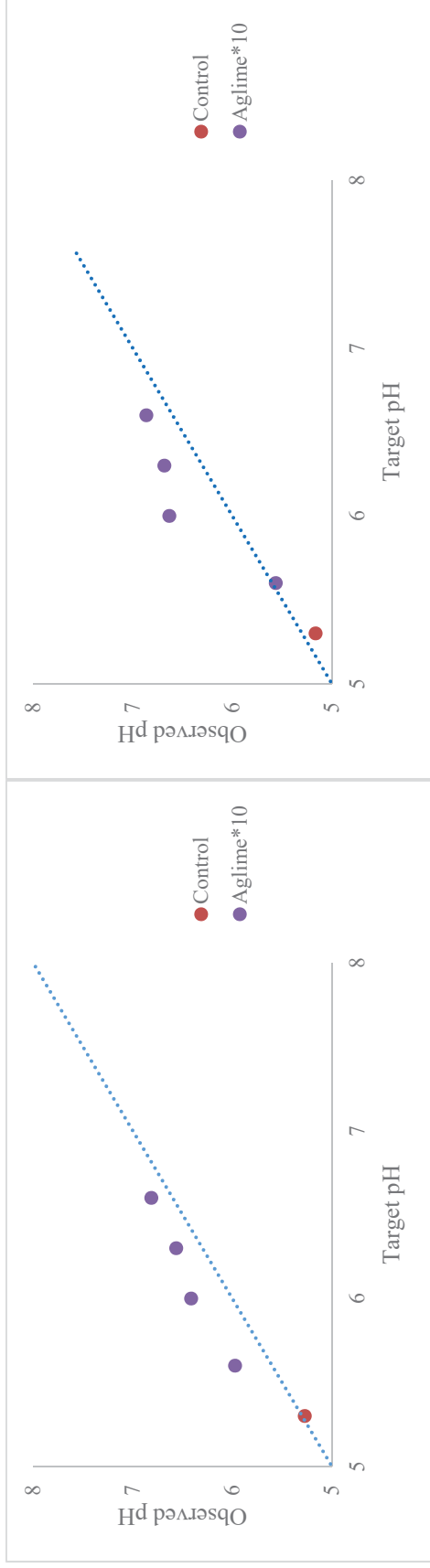


Figure 23 (left). Lincoln Wheat field pH of control and lime amendment plots after 139 days

Figure 24 (right). Lincoln Wheat field pH of control and lime amendment plots after 169 days

5 Cost-Benefit Analysis

Cost-benefit analysis is a useful tool for decision making around natural resource allocation, and in particular for deciding if proposed projects should go ahead (Department of Finance, 1991). A CBA involves valuing all costs and benefits that will occur both with and without the implementation of a project or strategy, as well as applying economic values to social and environmental costs and benefits and considering these within the analysis (Department of Finance, 1991). In this way, variables which may be considered as environmental externalities can be afforded a monetary value and accounted for. A CBA was designed to determine the economic viability of lime and compost amendment use for regulating Cd bioavailability at each site under potato production. This involved consideration of costs associated with the purchase, transportation and spreading of lime and compost specific to each field site, as well as the benefits of potato revenue. This also emphasises the importance of ascertaining a target pH in a field situation, as this analysis used a target pH of 6.4 from which lime application rates and their associated costs were calculated. From this CBA, conclusions on the economic viability of the proposed mitigation strategy can be drawn, and recommendations made on the suitability of this strategy at each field site.

5.1 Methodology

5.1.1 Criteria for Viability

Under the ‘cost-benefit rule’ (Department of Finance, 1991, p. ix) a project is deemed acceptable and worthwhile where net social benefits (or the Net Present Value (NPV)) equate to a positive value. The NPV is the final result of the analysis, and represents the overall returns or losses likely to occur as a result of the project. Calculating the NPV entails the use of ‘present values’ (PVs): As over time the value of currency decreases in what it is able to buy, a discount rate is used to calculate the equivalent PV of future costs and benefits (Department of Finance, 1991). A discount rate of 6% was used in this CBA to calculate PVs, a default rate recommended by The Treasury (2016). Appendix D details this discount factor and its associated discount rates and PV equations. The NPV for each scenario was calculated using the Microsoft Excel formula.

5.1.2 The Project Scenario

The assumptions in this CBA were as follows: A 50 ha commercial potato plot exists at each location. If Cd residue levels in potatoes exceed international food standards, the entire crop will be rejected by export markets and thus 100% of the potential revenue will be lost. Therefore, the alternative situation in this analysis is one in which no benefits or costs exist, generating an NPV

of 0. This is the basis for comparison of the current CBA assessing the proposed mitigation strategy.

5.1.3 Determination of Costs and Benefits

A pH target of 6.4 was used to calculate lime amendment rates and costs for each site. This value chosen due to several considerations. That is, Cd bioavailability decreases at a higher pH, and is particularly immobile at a pH of ≥ 7.5 (Kabata-Pendias & Mukherjee, 2007). However, the optimal pH range for potato cultivation in NZ soils sits between 5.4-5.8 (Hill Laboratories, 2002). While potatoes may be easily cultivated at a soil pH of 6.0, this risks the development of the bacterial disease potato scab, and thus a lower pH is considered optimal (Hill Laboratories, 2002). Furthermore, as NZ soils are typically acidic, raising the soil pH to the optimal value for Cd immobilisation of ≥ 7.5 is likely to be both impractical and expensive due to the vast quantities of lime which would be required to effect such a pH change – Ravensdown (2016) recommends approximately 1 t ha⁻¹ of aglime for every desired 0.1 pH unit increase. Therefore, a compromise had to be reached between an optimal pH for Cd immobilisation and an appropriate range for potato cultivation.

Of the target pH values used in the field trials, 6.3 appeared an appropriate compromise between a higher pH which may result in potato scab (6.7 and 7), and a lower pH which may not sufficiently result in Cd immobilisation (5.6 and 6). However, within the incubation experiments detailed in Chapter 4, readings for the target of 6.3 within the Pukekawa, Manawatu and Lincoln Potato soils at day 10 revealed higher-than-target pH values, which were closer to the value of 6.4 than 6.3. Therefore 6.4 was adopted as the pH target value for use in this CBA, by which required aglime applications could be calculated using the pH buffer curve and incubation data. As aglime*10 represented the most effective liming amendment for ascertaining a target pH during incubation experiments, this was the amendment chosen for the purposes of this CBA. The aglime application rates for each site, along with the other factors considered in this CBA are detailed in Table 14.

Table 14. Factors considered within the CBA and their associated values

Factor		Value
Potato yield (t ha ⁻¹)		60
Potato farmgate revenue (\$ t ⁻¹)		280.00
Aglime requirement (t ha ⁻¹)	Pukekawa	3.90
	Manawatu	6.26
	Lincoln	7.70
Aglime supply and cart rate(\$ t ⁻¹)	Pukekawa	42
	Manawatu	36
	Lincoln	45
Aglime spreading rate (\$ t ⁻¹)	Pukekawa	18.61
	Manawatu	17.38
	Lincoln	17.38
Compost requirement (t ha ⁻¹)		25
Compost cost (\$ t ⁻¹)		12.50
Compost spreading rate (\$ t ⁻¹)		8.00
Compost transport rate (\$ km ⁻¹)		4.25

Compost requirements were determined by the application rate of treatments in the field trials, which used either a high (50 t ha⁻¹) or medium (25 t ha⁻¹) rate of compost addition. However, only the medium rate was used to determine compost supply, spreading and transport costs within the CBA, as this rate of application comprises four of the five compost treatments in the current field trials with the high treatment rate only used without concurrent lime addition. Thus the high application rate is less likely to be implemented as a result of this study, due to the aim of utilising both lime and compost to effect both pH and OM content changes within the soil. Additionally, the medium rate of application is specified by Horrocks et al. (2013) as being effective at improving OM content over a three-year cropping rotation with reapplications recommended every three-four years at the same application rate.

Average potato yields for Canterbury, Manawatu and Pukekohe were sourced from Potatoes NZ Inc. (2015, p. 38). The *Lincoln University Financial Budget Manual 2014* (Askin & Askin, 2014) provided values for potato farmgate revenue and aglime spreading rates. To quantify the costs and benefits at the farm-scale, farmgate potato prices were used rather than export prices. Furthermore – due to the farm-scale focus of this analysis – GST was not included and all benefits were pre-tax.

Aglime supply and cart rates were provided by C. Telfer of Bulk Lines Ltd. (personal communication, 24th November 2016). Combined supply and cart rates were used over individual supply and transportation rates as this proved to be the more economic option. Compost supply, transportation and spreading rates were supplied by G. Wright of Living Earth Compost Suppliers (personal communication, November 22nd, 2016).

Effects on potato yield due to lime and compost additions were not considered as part of this analysis, as Horrocks et al. (2013) state that yield responses were not observed in their study

as a result of compost amendment due to the high fertiliser inputs which occur as part of typical vegetable production, which worked to maintain yields at typical levels.

Based on the field trial work by Horrocks et al. (2013), it was assumed that compost would continue to bind Cd for up to three years in soil, and thus reapplication at the original rate would occur at the end of every three years. The same logic was used for lime reapplication timing, with the assumption that both lime and compost should be applied together to maintain a consistent effect throughout the employment of this strategy. This assumption concerning compost's longevity in soil is also supported by Al Mamun et al. (2016b).

5.1.4 Determination of the Project's Net Present Value

Based on the assumptions and values presented in Table 14, total costs of mitigation implementation and total benefits from potato revenue were quantified for each field site. Costs and benefits were discounted using the discount rate of 6%, and their PV quantified. PV costs were subtracted from PV benefits for each year, to give the discounted net benefits. This value is also equal to the net cash flow (total benefits minus total costs) multiplied by the discount factor. The sum of the discounted net benefits at the end of the projected period was equal to the NPV. Following the criteria used in this analysis, if the $NPV \geq 0$, the strategy was considered economically viable (Department of Finance, 1991). As an NPV of 0 also represents the situation that would occur if this mitigation were not implemented— that is, if Cd residue levels in food stuffs exceeded international food standards and thus faced market rejection as a result of excessive exchangeable Cd concentrations in soil— this is the criteria by which the implementation of this mitigation can be compared to a base scenario in which all exports from these sites would be lost.

For the reasons stated above (section 5.1.3) concerning the longevity of amendments in soil for up to three years, this CBA was undertaken to a three-year time-period. Long-term employment of this strategy effectively equates to repeating this initial project (applying lime and compost to soil) every three years. Thus, to expand this CBA out to a longer time-period would involve repeating this analysis (with costs of amendment reapplication in years four, seven, 10 and so on) and multiplying the net cash flow by the discount factor for each year (see Appendix D for discount factors associated with the applied 6% discount rate) to give the discounted net benefits and thus the total NPV at any given time-period. In practice, this would simply increase or decrease the NPV by a set amount every three years without giving any further insight into the long-term efficiency of such a project.

5.1.5 Sensitivity Analysis

Sensitivity analysis is a way to account for uncertainty or potential fluctuations in costs and benefits which may affect the final NPV should they change (Gittinger, 1982). A sensitivity analysis is generally undertaken as one of the final steps in a CBA, and simply changes one of the costs or benefits to reflect a worsened scenario than was envisioned in the original analysis. In CBAs concerned with agricultural projects, there are four main areas of uncertainty which may fluctuate and thus it is useful to base a sensitivity analysis around one of these: price; delay in implementation; cost overrun; and yield (Gittinger, 1982). In this analysis, potential fluctuations in potato yield (as current yields are reported at between 50-60 t ha⁻¹ (Potatoes NZ Inc., 2015)) were used to undertake a sensitivity analysis. The original CBA used a best-case assumption of potato yields at 60 t ha⁻¹, while a sensitivity analysis was undertaken using a worst-case assumption of 50 t ha⁻¹ to determine whether this mitigation would be viable should farmers face worst-case scenarios and fluctuations in crop yields.

5.2 Results

Table 15,

Table 16 and Table 17 detail the results of the CBA for each site over a three-year time-period. The overall NPV for the proposed mitigation at each site after this time is detailed. As shown in Table 15, the farmgate potato revenue (the same across sites) constitutes the total benefits, generating \$840,000.00 revenue (before the consideration of PVs) per year. The costs of lime and compost purchase and transportation are detailed, while spreading for both lime and compost are considered together to constitute a single cost. Total costs are calculated from all of these factors combined. As costs would be paid at the start of year one and benefits received in the form of revenue at the conclusion of each year, costs are detailed in year zero while benefits occur in years one-three. After PVs have been applied, total costs are subtracted from total benefits for each year, generating the project's discounted net benefits over the three-year period. The NPV is equal to the sum of this, representing the total return which would occur over the life of this project.

The NPV for the 50 ha Pukekawa site after three years is \$2,207,619.56; the 50 ha Manawatu site sits at \$2,200,833.89 at the end of year three; while the NPV for the Lincoln site over 50 ha after this time-period is \$2,195,555.25. As the analysis for all sites results in a positive NPV, this means that implementing this strategy is a better option than non-implementation (in which case the NPV = 0, due to there being no costs of implementation and no benefits as all exports would exceed Cd food standards and thus face market rejection). Therefore, it can be concluded that mitigation is considered to be economically viable and recommended for all sites.

The mitigation is most profitable at the Pukekawa site, with the Lincoln site generating the lowest NPV. The differences in results between sites are attributed largely to the lime requirements of each soil based on their native pH. As the Pukekawa site's buffer curve-generated the highest native pH of 6.0, it requires less lime to reach the target pH of 6.4 and thus faces less costs compared with the Lincoln and Manawatu sites. While the Manawatu site has the lowest lime supply and cart rate of \$36.00t⁻¹ (compared with \$42.00t⁻¹ and \$45.00t⁻¹ for the Pukekawa and Lincoln sites respectively) due to its proximity to a lime stone quarry, it requires a greater amount of lime due to its native pH of 5.78 (from the pH buffer curve), and thus incurs greater costs resulting in a lower NPV. The Lincoln site has both the lowest native pH (5.66) generated by the pH buffer curve and thus the greatest aglime requirement, as well as the greatest lime supply and cart rates, and therefore has the lowest NPV. Despite these differences, implementation of this mitigation strategy to protect potato yields and exports is recommended for all sites as this analysis shows it will result in protected earnings on the farm-scale, as opposed to 100% loss of yields and revenue if the strategy is forgone and Cd residue levels in foodstuffs exceed international food safety standards.

Table 15. Cost-benefit analysis of mitigation at the Pukekawa site, detailing benefits from potato revenue, costs of mitigation, present values of total costs and benefits, the project's net cash flow and the overall NPV

Year	Benefits			Costs					Net Cash Flow (Benefits- Costs)	Discount Factor 6%	Discounted Net Benefits	
	Farmgate potato sales	Total Benefits	PV Benefits	Lime Supply & Cart	Compost	Compost Transport	Spreading	Total Costs				PV Costs
0	-	-	-	8,192.10	15,625.00	263.50	13,629.88	37,710.48	37,710.48	-37,710.48	1.0000	-37,710.48
1	840,000.00	840,000.00	792,452.83	-	-	-	-	-	-	840,000.00	0.9434	792,452.83
2	840,000.00	840,000.00	747,597.01	-	-	-	-	-	-	840,000.00	0.8900	747,597.01
3	840,000.00	840,000.00	705,280.20	-	-	-	-	-	-	840,000.00	0.8396	705,280.20
TOTALS	2,520,000.00	2,520,000.00	2,245,330.04	8,192.10	15,625.00	263.50	13,629.88	37,710.48	37,710.48	2,482,289.52		2,207,619.56
NPV												\$2,207,619.56

Table 16. Cost-benefit analysis of mitigation at the Manawatu site, detailing benefits from potato revenue, costs of mitigation, present values of total costs and benefits, the project's net cash flow and the overall NPV

Year	Benefits			Costs					Net Cash Flow (Benefits- Costs)	Discount Factor 6%	Discounted Net Benefits	
	Farmgate potato sales	Total Benefits	PV Benefits	Lime Supply & Cart	Compost	Compost Transport	Spreading	Total Costs				PV Costs
0	-	-	-	11,262.24	15,625.00	2,171.75	15,437.16	44,496.15	44,496.15	-44,496.15	1.0000	-44,496.15
1	840,000.00	840,000.00	792,452.83	-	-	-	-	-	-	840,000.00	0.9434	792,452.83
2	840,000.00	840,000.00	747,597.01	-	-	-	-	-	-	840,000.00	0.8900	747,597.01
3	840,000.00	840,000.00	705,280.20	-	-	-	-	-	-	840,000.00	0.8396	705,280.20
TOTALS	2,520,000.00	2,520,000.00	2,245,330.04	11,262.24	15,625.00	2,171.75	15,437.16	44,496.15	44,496.15	2,475,503.85		2,200,833.89
NPV												\$2,200,833.89

Table 17. Cost-benefit analysis of mitigation at the Lincoln site, detailing benefits from potato revenue, costs of mitigation, present values of total costs and benefits, the project's net cash flow and the overall NPV

Year	Benefits		Costs					Total Benefits	PV Benefits	Lime Supply & Cart	Compost	Transport	Spreading	Total Costs	PV Costs	Net Cash Flow (Benefits-Costs)	Discount Factor 6%	Discounted Net Benefits	
	Farmgate potato sales																		
0	-	-	17,330.85	15,625.00	125.38	16,693.56	49,774.79	49,774.79	-	-	-	-	-	-	-	-	1.0000	-49,774.79	
1	840,000.00	840,000.00	-	-	-	-	-	792,452.83	-	-	-	-	-	-	-	840,000.00	0.9434	792,452.83	
2	840,000.00	840,000.00	-	-	-	-	-	747,597.01	-	-	-	-	-	-	-	840,000.00	0.8900	747,597.01	
3	840,000.00	840,000.00	-	-	-	-	-	705,280.20	-	-	-	-	-	-	-	840,000.00	0.8396	705,280.20	
TOTALS	2,520,000.00	2,520,000.00	17,330.85	15,625.00	125.38	16,693.56	49,774.79	2,245,330.04	17,330.85	15,625.00	125.38	16,693.56	49,774.79	49,774.79	2,470,225.21			2,195,555.25	
NPV																			\$2,195,555.25

5.2.1 Sensitivity Analysis

The results of the sensitivity analysis, using a potato yield of 50 t ha⁻¹ for each site, are detailed in Table 18, Table 19 and Table 20 below. The NPVs of the Pukekawa, Manawatu and Lincoln sites using a 50 ha plot over three years are \$1,833,397.88, \$1,826,612.21 and \$1,821,333.57 respectively. As shown in Table 18, the difference between this sensitivity analysis and the original is the value of the benefits, as a result of reduced potato yields. In this situation, a yield of 50 t ha⁻¹ results in annual benefits of \$700,000.00 at the end of years one-three, compared to \$840,000.00 with yields of 60 t ha⁻¹. This reduces the overall NPV, however does not make the project economically unviable. As the NPV of all sites here is greater than 0, this remains a better option than foregoing implementation, in which case the NPV would be 0.

Again, the Pukekawa site produces the highest NPV and the Lincoln site the lowest. The differences in value between sites remain the same as in the original analysis, as the only affected parameter here is potato revenue, which is equal for all sites. The results of this sensitivity analysis are positive for each site, and consequently potential fluctuations in potato yield are unlikely to affect the viability of this proposed strategy. Although yield reductions, should they occur, will result in a lower overall return from the project, it remains a more economical and attractive alternative than forgoing implementation, and consequently losing all revenue due to exceedance of food standard guidelines for Cd residue. Therefore, implementation of this strategy using lime and compost amendments to regulate Cd bioavailability in soils is recommended at all three of the sites under consideration, with the recognition that fluctuations in yield will not affect the economic efficiency of this strategy.

Table 18. Cost-benefit sensitivity analysis for the Pukekawa site using a potato yield of 50 t ha⁻¹, detailing benefits from potato revenue, costs of mitigation, present values of total costs and benefits, the project's net cash flow and the overall NPV

Year	Benefits			Costs				Total Costs	PV Costs	Net Cash Flow (Benefits-Costs)	Discount Factor 6%	Discounted Net Benefits
	Farmgate potato sales	Total Benefits	PV Benefits	Lime Supply & Cart	Compost	Compost Transport	Spreading					
0	-	-	-	8,192.10	15,625.00	263.5	13,629.88	37,710.48	37,710.48	-37,710.48	1.0000	-37,710.48
1	700,000.00	700,000.00	660,377.36	-	-	-	-	-	-	700,000.00	0.943396	660,377.36
2	700,000.00	700,000.00	622,997.51	-	-	-	-	-	-	700,000.00	0.889996	622,997.51
3	700,000.00	700,000.00	587,733.50	-	-	-	-	-	-	700,000.00	0.839619	587,733.50
TOTALS	2,100,000.00	2,100,000.00	1,871,108.36	8,192.10	15,625.00	263.50	13,629.88	37,710.48	37,710.48	2,062,289.52		1,833,397.88
NPV												\$1,833,397.88

Table 19. Cost-benefit sensitivity analysis for the Manawatu site using a potato yield of 50 t ha⁻¹, detailing benefits from potato revenue, costs of mitigation, present values of total costs and benefits, the project's net cash flow and the overall NPV

Year	Benefits			Costs				Total Costs	PV Costs	Net Cash Flow (Benefits-Costs)	Discount Factor 6%	Discounted Net Benefits
	Farmgate potato sales	Total Benefits	PV Benefits	Lime Supply & Cart	Compost	Compost Transport	Spreading					
0	-	-	-	11,262.24	15,625.00	2,171.75	15,437.16	44,496.15	44,496.15	-44,496.15	1.0000	-44,496.15
1	700,000.00	700,000.00	660,377.36	-	-	-	-	-	-	700,000.00	0.9434	660,377.36
2	700,000.00	700,000.00	622,997.51	-	-	-	-	-	-	700,000.00	0.8900	622,997.51
3	700,000.00	700,000.00	587,733.50	-	-	-	-	-	-	700,000.00	0.8396	587,733.50
TOTALS	2,100,000.00	2,100,000.00	1,871,108.36	11,262.24	15,625.00	2,171.75	15,437.16	44,496.15	44,496.15	2,055,503.85		1,826,612.21
NPV												\$1,826,612.21

Table 20. Cost-benefit sensitivity analysis for the Lincoln site using a potato yield of 50 t ha⁻¹, detailing benefits from potato revenue, costs of mitigation, present values of total costs and benefits, the project's net cash flow and the overall NPV

Year	Benefits		Costs					Total Costs	PV Costs	Net Cash Flow (Benefits- Costs)	Discount Factor 6%	Discounted Net Benefits
	Farmgate potato sales	Total Benefits	PV Benefits	Lime Supply & Cart	Compost	Compost Transport	Spreading					
0	-	-	-	17,330.85	15,625.00	125.38	16,693.56	49,774.79	49,774.79	-49,774.79	1.0000	-49,774.79
1	700,000.00	700,000.00	660,377.36	-	-	-	-	-	-	700,000.00	0.9434	660,377.36
2	700,000.00	700,000.00	622,997.51	-	-	-	-	-	-	700,000.00	0.8900	622,997.51
3	700,000.00	700,000.00	587,733.50	-	-	-	-	-	-	700,000.00	0.8396	587,733.50
TOTALS	2,100,000.00	2,100,000.00	1,871,108.36	17,330.85	15,625.00	125.38	16,693.56	49,774.79	49,774.79	2,050,225.21		1,821,333.57
NPV												\$1,821,333.57

5.3 Environmental Management: How Realistic is this Mitigation Strategy?

5.3.1 Soil pH and Potato Scab

Although the proposed mitigation strategy is economically viable when compared to a situation in which mitigation is not applied, there are several factors which should be considered before this strategy is implemented on a larger scale. The first is that raising the soil pH to >6.0 risks the development of potato scab, which has potential to have negative outcomes for potato revenue – although potato scab does not affect yield, it limits the marketability of the crop due to the negative cosmetic effect on tubers (Merz, 2008). The occurrence of potato scab at a soil pH of 6.4 at each site will remain unknown until the completion of field trials however, and should be addressed in future work.

5.3.2 Compost Supply

In order for compost to be used as a Cd mitigation, it must be of consistent pH and composition so as to have a consistent effect across all application sites (Al Mamun et al., 2016b). If this strategy were to be implemented on a national scale, there must be a sufficient, consistent reliable supply of compost available for purchase and transportation. The compost suppliers used in this analysis, Living Earth, could not provide for such a national demand (G. Wright, personal communication, 28th November 2016).

Living Earth compost consists of municipal green waste, and contains on average 52% OM, 30% C, 2.3% N, 0.39% P, 273 mg kg⁻¹ Zn, 9.36 mg kg⁻¹ Fe, and a pH of 7.5 (Living Earth, n.d.). While other compost suppliers operate throughout NZ, their products differ in source material and composition (for example, Cypress Sawmill, an Auckland based company, markets compost sourced from sawdust and wood shavings, while Tui, based in Mt Maunganui, provide compost composed of blood, bone and gypsum with a different nutrient composition to that of Living Earth compost (Cypress Sawmill, n.d.; Tui, n.d.)). Thus within NZ there is a limited supply of suitable, consistent compost products. Consequently, the supply of such products would need to increase, which may occur as a result of increased demand were this strategy to be implemented on a national scale.

5.3.3 On-farm Considerations

Practical considerations around the implementation of this strategy should also be considered. Although labour costs around amendment application have been factored into the CBA (under spreading costs), and thus accounted for, the time involved in this application is more difficult to quantify on a monetary basis and thus has been omitted from the analysis. Based on application

procedures throughout the field trial work, application of amendments takes approximately one day, and once applied amendments should be incorporated into soil via use of a rotary hoe or similar. Weather conditions need to be appropriate (that is, neither heavily raining nor too windy) for such application, and sufficient time (approximately 2-4 weeks based on field trial work) should be left between application and planting, so that amendments are sufficiently incorporated and active within the soil during plant growth. Thus weather conditions need to be appropriate for the time-period between (and inclusive of) amendment application and planting, and during the period post-planting to allow for crop germination. This requirement for such a period of appropriate weather may lead to delays in planting, as farmers may have to wait a period of time before amendments can be applied and crops can be planted. This may result in inconveniences and changes to normal cropping rotations. Thus it will be important for farmers to have a pre-emptive approach should they need to implement this strategy, leaving plenty of time available and taking weather forecasts into consideration when planning amendment application.

5.3.4 Towards a Key Step: Achieving a Target pH

Soil pH management presents challenges for farmers, due to the variability in characteristics of NZ soils. In particular, the production of a specific target soil pH can be a difficult task, which usually entails calculating the soil's pH buffering capacity (Ketterings et al., 2010). The pH incubation and field pH results presented in Chapter 4 highlight the difficulty of accurately producing a target pH using liming materials. To test the efficacy of amendment rates at achieving a target pH in incubation experiments is a time-consuming task which requires a controlled environment with an incubator running at a constant temperature. This is difficult to achieve outside of a laboratory setting.

Required amounts of lime with which to achieve a specific pH depend on the native pH of the soil, and will vary across different soil types (Sime, 2001). As buffer curve-generated application rates to achieve a specific soil pH differ to in-field application rates, buffer curves require a degree of conversion before they can be used by farmers (Ketterings et al., 2010). They are, however, relatively quick to generate, producing results within 24 hours. Although pH incubation experiments may be conducted to test buffer curve application rates, this is a time-consuming process, which is neither practical nor realistic in an on-farm setting. Therefore, the development of a model by which to convert buffer curve-generated application rates to field-applicable application rates to produce a specific soil pH would be an innovative step for farming management in NZ. This would allow farmers greater control over soil acidity, which would in turn allow for improved management of Cd bioavailability.

5.3.4.1 Deriving A Method for Improved Use of pH Buffer Curve Data

To investigate whether such a model could be determined for the soils under study, field application rates for specific pH values were compared to those generated by the pH buffer curve for the Pukekawa and Lincoln Wheat soils as field pH data was available for these sites. All in-field application rates and products detailed here are those used in field trial experiments. In-field applications used in field trial work at each site consisted of lime flour (98% CaCO₃). A relationship was found between the field and buffer curve-generated lime application rates within the Pukekawa soil for the pH range of 6.00-7.28 (Figure 25).

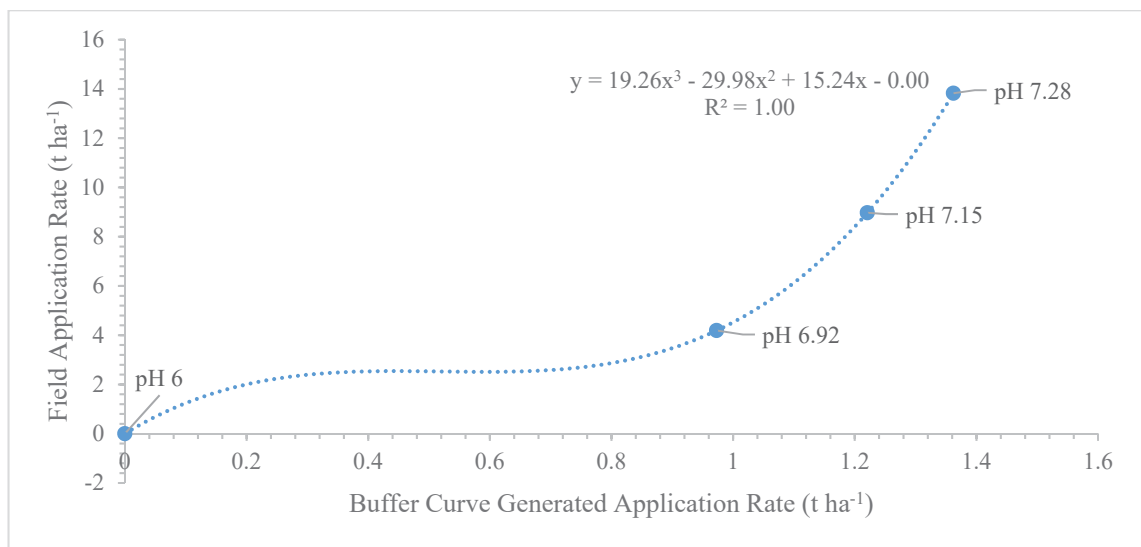


Figure 9. Relationship between buffer curve-generated and field application rates of lime to achieve a target pH in Pukekawa soil

The relationship between the buffer curve and field application rate to generate a fixed pH gives a relatively good degree of confidence for an extrapolation of buffer curve values to field lime rates. In the context of the CBA described in this chapter, this is considered to be a useful tool for farmers who do not have time to perform lengthy incubation experiments to test their application rates. In this instance, a buffer curve could be generated (as described in section 4.1.3) which can be used to calculate the recommended rate of lime to achieve a specific pH. For example, to achieve a target pH of 6.4 in this soil, the buffer curve (shown in Figure 4) can be used to calculate a recommended lime application of 0.42 t ha⁻¹. Figure 25 could then be consulted to determine how this buffer curve rate can be converted to a field rate with which to achieve this pH of 6.4. To do this, the model equation may be used to calculate a field rate equal to 2.54 t ha⁻¹.

However, as this is designed as a quick and efficient tool for farmers, it is also possible to read the graph by sight using the trendline, by finding the value of 0.42 on the x-axis and finding where the trendline at this point measures on the y-axis. This provides an in-field application rate with a certain degree of accuracy which can then be used to achieve a targeted soil pH in this Pukekawa soil.

The curve fitted to this data (a 3rd degree polynomial) represents an empirical relationship between field and buffer curve-generated application rates and allows for the solving of the field application rates based on any buffer curve-generated lime application rate. It is not advocated as an accurate theoretical model for this system. As there is a clear relationship between these application rates, this data could be used to determine appropriate field application rates from buffer curve data regardless of the equation represented by this curve.

When the field and buffer curve-generated application rates were compared for the Lincoln Wheat soil, a different situation emerged. This is shown in Figure 26 below. No clear trend or relationship is observed here, thus, a model such as that used above for the Pukekawa soil could not be applied to this soil. No polynomial of any order could be fitted to this data set.

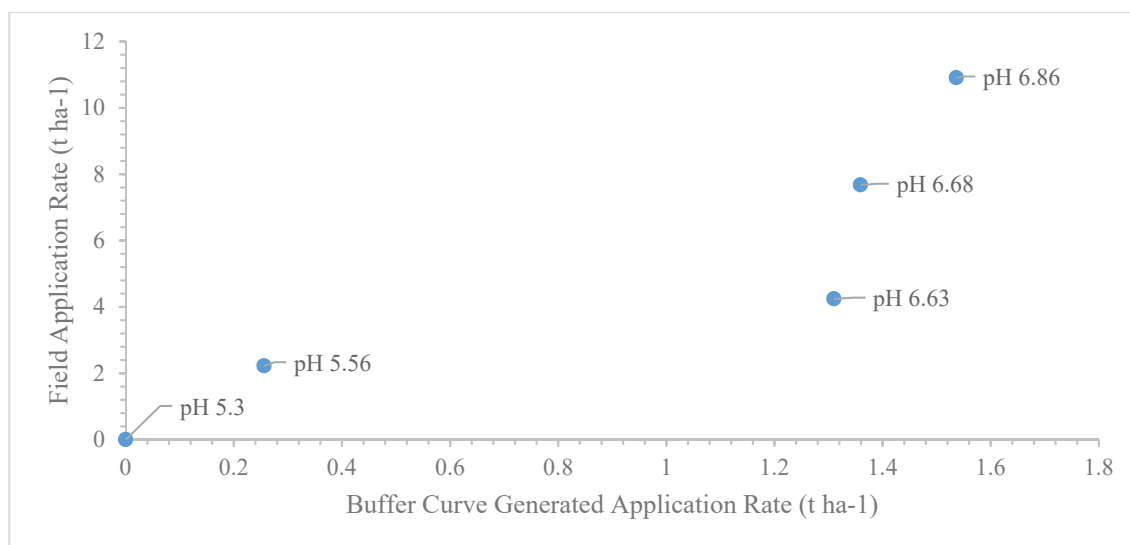


Figure 10. Relationship between buffer curve-generated and field application rates of lime to achieve a target pH in Lincoln Wheat soil

Figure 26 shows a large difference between the buffer curve-generated and field data for this soil, particularly between the points at pH 5.56 and 6.63. This suggests a difference in buffering between laboratory and field situations, with a large amount of field buffering happening relative to the buffer curve experiment (the spread of data in Figure 26 is representative

of a buffer curve). Within the site characterisation (Chapter 3), this soil exhibited a very low pH (mean = 4.93) which suggests the soil may have been acidified. This may have affected the soil's pH buffering capacity, as large amounts of acid which have been added to the soil then need to be neutralised before a pH increase can occur. This would result in the need for large quantities of lime to neutralise this acid, before then effecting a pH increase in this soil. Once this acid has been neutralised however, relatively smaller quantities of lime would then be required to further increase the soil pH.

Table 21 illustrates that this soil acidification and resultant change to buffering capacity is likely the case for this Lincoln Wheat soil, as to effect a pH change from 5.3 to 5.56 requires a lime amendment 8.68 times that generated by the buffer curve. However, to produce a change from pH 5.3 to 6.63 requires a lime amount of 3.24 times that generated by the buffer curve. This suggests a high amount of buffering within the soil at lower pH levels. The full reasons behind this possible soil acidification and impact on pH buffering are beyond the scope of this research. Thus, no rule can be derived for this soil for which to convert buffer curve-generated liming application rates to rates for use in field in order to achieve a targeted soil pH. Any field rates would need to be experimentally determined based on long-term soil incubations.

Table 21. pH changes in the Lincoln Wheat soil during field trial work, and their associated lime application rates

Starting pH	Final Field pH	pH Change	In-Field Lime Flour (98% CaCO ₃) Application Rate (t ha ⁻¹) 'x'	Buffer Curve-generated Lime Flour (98% CaCO ₃) Application Rate (t ha ⁻¹) 'y'	Buffer Curve to Field Relationship 'x/y'
5.3	5.56	0.26	2.22	0.26	8.68
	6.63	1.33	4.24	1.31	3.24
	6.68	1.38	7.68	1.36	5.65
	6.86	1.56	10.91	1.54	7.10

5.3.4.2 Implications for Cost-Benefit Analysis

A model was derived for the conversion of buffer curve to in-field liming application rates for the Pukekawa soil, however no such method could be determined for the Lincoln Wheat soil. This emphasises the soil specific nature of pH buffering capacity and thus the need for further research into targeted management guidelines for specific soils. The derivation of such a method does not appear possible for all soils. It is evident that lime application rates to achieve a target pH are non-uniform across soil types, and thus further work on the possibility and development of such a method for use in a range of horticultural soils would be beneficial.

The derivation of this conversion method for the Pukekawa soil highlights opportunities for improved soil pH management. When applied to the mitigation strategy under investigation in the CBA, this method may be used to determine lime amendment rates for the soil pH target of 6.4 as described above with a relatively high degree of confidence, making implementation of this strategy both easier and more efficient for farmers. As shown with the field pH data from field trial work, using buffer curve data to calculate amendment rates can produce pH values which are not exactly in line with targets. This method however presents a way with which to correct this buffer curve-generated data, and achieve a soil pH for specific purposes such as Cd immobilisation with a degree of accuracy. This is also likely to decrease on-farm costs associated with liming, due to the accuracy of this model at determining required rates. This may further provide benefits for crop cultivation, allowing farmers to accurately maintain a soil pH appropriate to the preferred growing conditions of certain crops.

If the Cd mitigation strategy is put into implementation on a national scale, this tool will be beneficial to farmers, especially if ideal pH values to decrease Cd bioavailability are imposed. As achieving a target pH in field is challenging without the use of prolonged incubation experiments, this presents a tool for farmers which can be used within 24 hours of creating a pH buffer curve. This is an innovative measure with which soil pH and thus Cd management can be improved in NZ's horticultural soils, to produce improved sustainability and export protection within this industry.

5.3.5 Recommendations for Implementation

Within the current framework of the TFMS, this mitigation strategy using lime and compost may face difficulties concerning implementation. As the TFMS takes into consideration total rather than exchangeable Cd concentrations in soil, it does not adequately account for risk and exposure pathways and thus provide a targeted approach to Cd management. Risk-based soil guidelines around Cd accumulation are necessary here for a more specific and targeted system to address this issue within a NZ context. Such guidelines may focus primarily on exchangeable rather than total Cd concentrations within soil, and the factors influencing Cd bioavailability. Under such a risk-based framework, this mitigation strategy may be used in a targeted manner at sites where exchangeable Cd concentrations are dangerously high, resulting in high Cd plant uptake and potential exceedance of food safety standards. This strategy will require industry-led implementation if it is to be adopted on a national level, and thus there is a clear need for specific, risk-based guidelines which can be communicated easily between all involved stakeholders.

6 Conclusions

Cadmium presents risks to NZ's horticultural industry, in the form of plant uptake from contaminated soils. When exported food products exceed international food standards for Cd residue, these products face market rejection which then has a reputational impact on NZ's wider horticultural exports. In order to address this risk, field trial work is being undertaken to test the efficacy of lime and compost amendments at regulating Cd bioavailability in soils through mechanisms of increased Cd adsorption and complexation, thus reducing plant uptake.

Soils from four study farm sites were characterised, including analysis of total and exchangeable Cd, pH, OM content, CEC, total and exchangeable Zn, Al and Fe oxides, total P, and total N. The highest total Cd concentration was observed in Pukekawa soil (0.52 mg kg^{-1}), which has undergone the longest land-use history of intensive fertiliser inputs. Both Lincoln Potato and Wheat soils exhibited low total Cd concentrations (0.13 mg kg^{-1}). While total Cd concentrations varied between sites, exchangeable Cd was very low ($0.01\text{-}0.02 \text{ mg kg}^{-1}$) at all sites. While this may appear to indicate that there is little risk of Cd plant uptake in these soils, some crops maintain a high Cd uptake despite low bioavailable concentrations in soils. This emphasises the need for targeted, soil and crop specific guidelines concerning Cd accumulation in horticultural soils.

pH incubation experiments on these soils were conducted to determine lime and elemental S amendment application rates for use in field trials. These were calculated using each soil's pH buffering capacity, a function of the soil's CEC. Incubation results after an extended time-period were compared to field pH readings at comparable time points. This showed no significant differences between the incubation and field situations at the time of the final readings. This suggests that the lime and S amendments interacted with the soils in comparable ways in both laboratory and field conditions, and that over time the soil reaches an equilibrium at which pH remains stable.

A CBA of the proposed mitigation strategy utilising lime and compost amendments to regulate Cd bioavailability within soils determined that this project is economically viable on all soils under consideration. Furthermore, this strategy would remain viable under varying conditions such as a decrease in potato yields at all sites. Practical considerations around this strategy are less certain however, as the time taken to amend plots with lime and compost may cause delays in farmers' rotations, thus good management and planning will be crucial for the success implementation of this strategy. National demand for a consistent, reliable supply of municipal compost is likely to increase should this strategy be implemented on a national scale, and as such the supply of this will need to increase to meet such a demand. The implementation of this strategy within the framework of the TFMS presents potential issues, due to the TFMS's

focus on total rather than bioavailable Cd concentrations in soil. Thus, for this strategy to be adopted on a national scale, clear risk-based guidelines concerning Cd accumulation in NZ soils must first be developed.

The development of a model by which to convert pH buffer curve-generated lime amendment rates to field application rates to produce a target pH represents a step towards improved pH management of NZ soils. A relationship between buffer curve-generated and field lime application rates was determined for the Pukekawa soil. This may be a useful tool for farmers using this soil for horticultural production, particularly if implementing the Cd mitigation strategy outlined in this document. This would allow farmers to quickly determine necessary lime amendment rates to achieve a specific soil pH with a degree of accuracy, without the need for lengthy incubation experiments. Further research on the development of such a method for other horticultural soil types is recommended.

A strategy which provides successful regulation of Cd bioavailability in horticultural soils would be of great benefit in maintaining the sustainability of NZ's horticultural industry. By protecting exports from food standard exceedance and market exclusion, this would address the reputational risk that occurs when food standards are breached. As NZ's national economy is reliant on such exports, this represents an important national interest which should continue to be addressed in future research.

7 References

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8 Appendices

Appendix A: Personal Communications

M. Taylor, Waikato Regional Council, email conversation, September 10th, 2015.

Information on the TFMS and NZ's Cd management strategy.

C. Telfer, Bulk Lines Ltd., phone conversation, November 24th, 2016.

Aglime supply and cart rates from quarry sites to field trial sites.

G. Wright, Living Earth Compost Suppliers, email conversation, November 22nd, 2016.

Living Earth compost supply, transportation and spreading rates from Christchurch (Lincoln site) and Auckland (Manawatu and Pukekawa sites) headquarters.

G. Wright, Living Earth Compost Suppliers., email conversation, November 28th, 2016.

Information on composition and availability of Living Earth municipal compost.

Appendix B: Soil Characterisation Data

Table B-1. Pukekawa soil characterisation results

Plot	Total Cd (mgkg ⁻¹)	Excha-ngeable Cd (mg kg ⁻¹)	pH	OM content (%)	CEC (meq 100g ⁻¹)	Total Zn (mg kg ⁻¹)	Excha-ngeable Zn (mg kg ⁻¹)	Al oxides (%)	Fe oxides (%)	Total P (%)	Total N (%)
1	0.46	0.01	6.31	5.24	16.12	216.12	0.06	0.76	0.37	0.15	0.27
2	0.48	0.01	6.33	5.44	16.12	207.85	0.00	0.71	0.33	0.14	0.25
3	0.45	0.01	6.34	5.32	15.03	207.57	0.00	0.74	0.33	0.14	0.26
4	0.42	0.02	5.92	5.30	12.68	189.90	0.12	0.86	0.39	0.14	0.27
5	0.42	0.02	5.95	5.36	14.29	214.88	0.12	0.76	0.36	0.13	0.26
6	0.47	0.01	6.38	5.32	15.53	202.70	0.00	0.79	0.39	0.15	0.26
7	0.51	0.01	6.20	5.40	16.78	207.77	0.06	0.75	0.37	0.16	0.25
8	0.47	0.01	6.16	5.46	14.83	197.54	0.00	0.80	0.39	0.15	0.27
9	0.54	0.02	6.21	5.58	17.85	195.27	0.06	0.73	0.36	0.15	0.27
10	0.52	0.01	6.15	5.54	16.30	183.45	0.00	0.79	0.40	0.15	0.27
11	0.45	0.01	6.36	5.42	17.37	184.10	0.00	0.71	0.30	0.16	0.26
12	0.42	0.02	6.04	5.36	18.35	186.38	0.06	0.72	0.35	0.15	0.26
13	0.53	0.01	6.21	5.58	17.37	201.55	0.00	0.67	0.32	0.15	0.27
14	0.52	0.01	6.34	5.38	17.00	198.60	0.00	0.75	0.35	0.16	0.25
15	0.54	0.01	6.27	5.62	16.79	201.20	0.00	0.80	0.41	0.17	0.27
16	0.60	0.02	6.20	5.70	17.57	190.90	0.00	0.76	0.36	0.18	0.28
17	0.57	0.01	6.24	5.70	17.52	195.53	0.00	0.82	0.37	0.18	0.27
18	0.59	0.01	6.31	5.62	18.90	178.54	0.00	0.79	0.34	0.16	0.28
19	0.49	0.01	6.40	5.52	14.82	178.99	0.06	0.86	0.40	0.16	0.28
20	0.60	0.01	6.26	5.70	17.39	181.50	0.06	0.77	0.38	0.19	0.27
21	0.53	0.02	6.31	5.72	18.63	194.06	0.00	0.83	0.37	0.18	0.28
22	0.50	0.01	6.40	5.52	18.58	196.58	0.00	0.83	0.36	0.18	0.26
23	0.61	0.01	6.31	5.60	18.95	206.96	0.06	0.75	0.33	0.21	0.28
24	0.53	0.01	6.37	5.78	19.01	198.56	0.00	0.80	0.35	0.18	0.27
25	0.61	0.02	6.28	5.74	16.60	206.31	0.06	0.89	0.41	0.17	0.27
26	0.58	0.01	6.35	5.62	18.80	205.68	0.00	0.76	0.36	0.17	0.26
27	0.64	0.01	6.44	5.52	18.69	190.12	0.00	0.80	0.39	0.18	0.27
28	0.51	0.01	6.26	5.76	19.59	192.04	0.00	0.80	0.37	0.17	0.27
29	0.57	0.01	6.39	5.50	20.00	190.33	0.00	0.82	0.42	0.17	0.25
30	0.57	0.01	6.36	5.68	20.66	205.95	0.00	0.83	0.41	0.17	0.25
Average	0.52	0.01	6.27	5.53	17.27	196.90	0.02	0.78	0.37	0.16	0.27
Standard deviation	0.06	0.004	0.13	0.15	1.83	10.23	0.04	0.05	0.03	0.016	0.01

Table B-2. Manawatu soil characterisation results

Plot	Total Cd (mg kg ⁻¹)	Excha-ngeable Cd (mg kg ⁻¹)	pH	OM content (%)	CEC (meq 100g ⁻¹)	Total Zn (mg kg ⁻¹)	Al oxides (%)	Fe oxides (%)	Total P (%)	Total N (%)
1	0.09	0.01	5.60	4.30	12.07	73.18	0.23	0.30	0.05	0.23
2	0.25	0.01	5.68	4.28	14.50	39.35	0.22	0.26	0.04	0.23
3	0.28	0.01	5.59	3.94	14.00	33.67	0.22	0.33	0.04	0.23
4	0.25	0.01	5.55	3.88	13.86	27.94	0.21	0.29	0.04	0.20
5	0.29	0.02	5.36	3.78	14.06	39.99	0.22	0.33	0.05	0.21
6	0.28	0.02	5.50	3.76	14.68	47.83	0.22	0.26	0.04	0.21
7	0.29	0.01	5.59	4.18	15.03	-	0.23	0.27	0.05	0.25
8	0.27	0.01	5.61	4.12	15.17	-	0.22	0.27	0.04	0.22
9	0.26	0.02	5.45	3.94	14.86	38.28	0.22	0.27	0.04	0.21
10	0.29	0.01	5.62	4.47	13.81	38.28	0.23	0.26	0.04	0.23
11	0.29	0.09	5.30	3.76	14.09	38.69	0.22	0.23	0.03	0.25
12	0.25	0.02	5.27	3.90	16.83	41.81	0.24	0.23	0.03	0.20
13	0.27	0.02	5.33	4.18	15.60	44.83	0.24	0.27	0.04	0.21
14	0.29	0.02	5.30	4.66	16.79	40.61	0.23	0.21	0.04	0.23
15	0.26	0.02	5.40	3.72	15.82	45.68	0.23	0.29	0.04	0.26
16	0.30	0.02	5.46	4.36	14.75	48.41	0.23	0.26	0.04	0.21

17	0.25	0.02	5.37	4.12	14.61	45.90	0.22	0.22	0.03	0.24
18	0.27	0.02	5.43	4.12	14.44	46.30	0.23	0.19	0.03	0.22
19	0.25	0.02	5.21	4.20	15.66	40.09	0.24	0.21	0.03	0.23
20	0.28	0.02	5.29	4.32	12.45	54.33	0.22	0.22	0.04	0.23
21	0.27	0.02	5.47	4.00	10.45	41.40	0.22	0.24	0.04	0.23
22	0.27	0.02	5.43	3.96	11.63	41.83	0.23	0.21	0.04	0.21
23	0.27	0.02	5.45	4.24	10.96	38.81	0.22	0.19	0.04	0.22
24	0.23	0.09	5.36	3.96	11.64	33.32	0.21	0.19	0.03	0.23
25	0.25	0.02	5.26	3.94	12.60	37.23	0.21	0.15	0.04	0.22
26	0.24	0.02	5.33	3.84	12.62	40.85	0.21	0.21	0.03	0.21
27	0.29	0.02	5.42	3.94	11.65	36.30	0.21	0.25	0.04	0.21
28	0.28	0.02	5.31	3.92	12.34	35.09	0.20	0.21	0.04	0.22
29	0.25	0.02	5.34	4.14	10.56	41.04	0.22	0.20	0.04	0.21
30	0.28	0.02	5.16	3.98	13.22	39.68	0.22	0.22	0.04	0.22
Average	0.26	0.02	5.41	4.06	13.69	41.81	0.22	0.24	0.04	0.22
Standard deviation	0.04	0.019	0.13	0.23	1.77	8.10	0.01	0.04	0.004	0.01

Table B-3. Lincoln Potato soil characterisation results

Plot	Total Cd (mgkg ⁻¹)	Exchangeable Cd (mg kg ⁻¹)	pH	OM content (%)	CEC (meq/100g)	Total Zn (mg kg ⁻¹)	Al oxides (%)	Fe oxides (%)	Total P (%)	Total N (%)
1	0.14	0.04	5.55	4.62	15.35	54.07	0.37	0.21	0.05	0.22
2	-	0.02	5.38	4.66	12.05	59.69	0.38	0.26	0.04	0.23
3	0.12	0.02	5.30	4.74	13.10	51.05	0.37	0.25	0.04	0.23
4	-	0.01	5.49	4.54	12.26	59.46	0.39	0.29	0.05	0.21
5	0.13	0.01	5.58	4.70	17.72	65.29	0.36	0.21	0.04	0.22
6	-	0.01	5.40	4.96	17.17	57.35	0.41	0.25	0.04	0.24
7	-	0.02	5.39	4.84	12.20	58.59	0.39	0.24	0.05	0.22
8	-	0.01	5.54	4.62	13.86	53.14	0.35	0.25	0.04	0.21
9	-	0.01	5.45	4.60	13.67	57.64	0.36	0.19	0.05	0.21
10	-	0.02	5.31	4.50	12.54	56.49	0.27	0.17	0.05	0.21
11	0.13	0.02	5.31	4.72	14.64	53.59	0.37	0.19	0.04	0.22
12	-	0.02	5.39	4.64	14.85	59.56	0.36	0.22	0.04	0.22
13	0.11	0.02	5.36	4.74	15.69	56.97	0.37	0.23	0.03	0.24
14	0.15	0.02	5.24	4.76	16.93	67.95	0.35	0.19	0.05	0.22
15	-	0.01	5.32	4.74	17.50	58.50	0.33	0.19	0.03	0.22
16	-	0.01	5.52	4.68	16.89	62.89	0.40	0.19	0.04	0.21
17	-	0.01	5.44	4.60	16.12	59.99	0.39	0.18	0.04	0.22
18	-	0.01	5.44	4.62	16.14	54.53	0.41	0.22	0.04	0.21
19	0.14	0.02	5.43	4.64	15.99	62.12	0.39	0.19	0.03	0.21
20	-	0.02	5.39	4.68	11.96	61.21	0.34	0.24	0.03	0.22
21	-	0.01	5.56	4.82	14.05	60.09	0.42	0.20	0.03	0.22
22	-	0.02	5.40	4.70	8.08	68.60	0.34	0.20	0.04	0.21
23	-	0.02	5.32	4.94	15.60	58.41	0.37	0.20	0.04	0.24
24	-	0.02	5.28	4.92	15.01	52.62	0.40	0.20	0.04	0.24
25	-	0.02	5.21	4.70	12.43	63.67	0.44	0.23	0.05	0.22
26	-	0.01	5.36	4.88	15.63	59.49	0.42	0.19	0.05	0.23
27	0.12	0.01	5.36	4.64	15.57	57.43	0.44	0.29	0.04	0.24
28	0.13	0.01	5.49	4.60	15.37	56.24	0.42	0.25	0.04	0.21
29	-	0.01	5.42	4.62	15.58	62.49	0.40	0.25	0.04	0.22
30	0.15	0.01	5.39	4.72	14.89	58.50	0.33	0.20	0.04	0.21
Average	0.13	0.02	5.40	4.70	14.63	58.92	0.38	0.22	0.04	0.22
Standard deviation	0.01	0.005	0.09	0.11	2.11	4.22	0.04	0.03	0.006	0.01

Table B-4. Lincoln Wheat soil characterisation results

Plot	Total Cd (mg kg ⁻¹)	Exchangeable Cd (mg kg ⁻¹)	pH	OM content (%)	CEC (meq 100g ⁻¹)	Total Zn (mg kg ⁻¹)	Exchangeable Zn (mg kg ⁻¹)	Al oxides (%)	Fe oxides (%)	Total P (%)	Total N (%)
1	0.13	0.03	4.96	4.68	16.39	69.33	7.21	0.23	0.31	0.04	0.24
2	0.17	0.02	5.11	4.60	16.55	85.63	6.92	0.22	0.34	0.04	0.22
3	0.14	0.03	4.89	4.44	16.09	125.33	7.97	0.21	0.28	0.04	0.22
4	0.13	0.02	4.88	4.24	-	105.79	6.98	0.21	0.27	0.04	0.21
5	0.12	0.02	4.76	4.36	-	97.84	6.79	0.20	0.28	0.03	0.22
6	0.13	0.02	5.04	4.20	-	121.84	6.86	0.19	0.25	0.03	0.21
7	0.11	0.02	4.95	3.94	-	85.92	7.09	0.19	0.24	0.03	0.20
8	0.13	0.02	4.96	3.72	-	113.65	6.79	0.17	0.22	0.03	0.19
9	0.10	0.02	4.96	3.92	-	81.01	6.74	0.18	0.23	0.04	0.20
10	0.12	0.02	5.11	4.26	-	107.13	6.61	0.19	0.24	0.03	0.22
11	0.12	0.02	5.08	4.40	-	90.88	7.06	0.20	0.26	0.03	0.22
12	0.14	0.02	4.98	4.06	-	117.74	6.80	0.19	0.22	0.03	0.21
13	0.10	0.02	4.82	3.82	-	97.68	6.98	0.18	0.23	0.03	0.21
14	0.12	0.02	4.90	4.04	-	112.43	7.18	0.18	0.27	0.03	0.20
15	0.12	0.02	4.92	4.26	-	117.65	3.80	0.19	0.23	0.03	0.21
16	0.13	0.02	4.76	4.38	-	100.62	6.79	0.22	0.27	0.03	0.22
17	0.15	0.02	4.89	4.52	-	108.31	8.11	0.21	0.26	0.04	0.24
18	0.11	0.02	4.89	4.56	-	104.27	6.74	0.20	0.28	0.04	0.23
19	0.15	0.02	5.04	4.58	-	93.26	6.70	0.20	0.24	0.03	0.23
20	0.14	0.02	4.88	4.54	-	92.48	6.67	0.21	0.25	0.04	0.22
21	0.12	0.03	4.88	4.62	15.02	98.46	7.72	0.21	0.25	0.04	0.23
22	0.14	0.03	4.97	4.52	15.21	111.11	7.57	0.21	0.25	0.04	0.22
23	0.16	0.02	4.91	4.50	14.96	115.62	7.72	0.21	0.27	0.04	0.22
24	0.11	0.03	4.79	4.48	14.55	122.89	7.48	0.23	0.25	0.03	0.22
25	0.12	0.02	4.86	4.32	14.22	111.99	7.71	0.22	0.23	0.03	0.21
26	0.14	0.02	4.89	4.36	13.58	122.59	4.88	0.21	0.24	0.03	0.21
27	0.12	0.02	5.00	4.02	13.29	119.15	5.42	0.20	0.24	0.03	0.20
28	0.12	0.03	4.88	3.96	11.62	114.56	6.64	0.20	0.21	0.03	0.19
29	0.12	0.02	5.00	4.04	11.75	106.90	6.82	0.19	0.24	0.03	0.19
30	0.09	0.02	5.05	4.26	12.79	101.49	6.79	0.21	0.27	0.02	0.22
Average	0.13	0.02	4.93	4.29	14.31	105.12	6.85	0.20	0.25	0.03	0.21
Standard deviation	0.02	0.003	0.09	0.26	1.63	13.83	0.87	0.01	0.03	0.005	0.01

Appendix C: Soil pH Buffering Capacity and Amendment Calculations

pH buffer results

Table C-1. pH buffer curve results for Pukekawa soil

Beaker	OH ⁻ /H ⁺ (mmol kg soil ⁻¹)	pH
1	60	8.83
2	50	8.65
3	40	8.33
4	30	8.22
5	20	7.60
6	0	6.00
7	-10	5.12
8	-20	4.51
9	-40	3.82
10	-60	3.38
(control)		

Table C-2. pH buffer curve results for Manawatu soil

Beaker	OH ⁻ /H ⁺ (mmol kg soil ⁻¹)	pH
1	60	8.48
2	50	8.21
3	40	7.92
4	30	7.45
5	20	7.00
6	0	5.78
7	-10	4.71
8	-20	4.17
9	-40	3.48
10	-60	3.05
(control)		

Table C-3. pH buffer curve results for Lincoln Potato soil

Beaker	OH ⁻ /H ⁺ (mmol kg soil ⁻¹)	pH
1	60	8.85
2	50	8.81
3	40	8.54
4	30	8.18
5	20	7.52
6	0	5.66
7	-10	4.66
8	-20	3.93
9	-40	3.25
10	-60	2.78
(control)		

Table C-4. pH buffer curve results for Lincoln Wheat soil

Beaker	OH ⁻ /H ⁺ (mmol kg soil ⁻¹)	pH
1	60	8.41
2	50	8.35
3	40	8.09
4	30	7.60
5	20	7.02
6	0	5.11
7	-10	4.18
8	-20	3.59
9	-40	3.05
10	-60	2.63
(control)		

pH buffer calculations

Table C-5. Soil buffering capacity and amendment application rate calculation table for Pukekawa and Manawatu soil

Column A	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I	Column J	Column K	Column L	
Pukekawa	pH change	Bcap (mmoles OH ⁻ soil ⁻¹ pH unit ⁻¹)	moles OH ⁻ ha ⁻¹	moles CaCO ₃ and Ca(OH) ₂ ha ⁻¹ pH unit ⁻¹	CaCO ₃ 80% kg ha ⁻¹	kg aglime ha ⁻¹	aglime*1 0 (kg ha ⁻¹)	aglime*2 0 (kg ha ⁻¹)	Ca(OH) ₂ 90% kg ha ⁻¹	kg hydrated lime ha ⁻¹	hydr. lime*10 (kg ha ⁻¹)	hydr. lime*20 (kg ha ⁻¹)
		3.64	6,241.68	3,120.84	312.08	390.10	3,901.05	7,802.09	230.94	256.60	2,566.02	5,132.04
		8.50	14,563.91	7,281.95	728.20	910.24	9,102.44	18,204.89	538.86	598.74	5,987.38	11,974.77
		12.15	20,805.58	10,402.79	1,040.28	1,300.35	13,003.49	26,006.98	769.81	855.34	8,553.41	17,106.81
pH change	Bcap (mmoles H ⁺ kg soil ⁻¹ pH unit ⁻¹)	moles H ⁺ ha ⁻¹	moles S ha ⁻¹ pH unit ⁻¹	S 100% kg ha ⁻¹	S*3 (kg ha ⁻¹)							
	4.86	8,322.23	4,161.12	133.16	399.47							
Manawatu	pH change	Bcap (mmoles OH ⁻ soil ⁻¹ pH unit ⁻¹)	moles OH ⁻ ha ⁻¹	moles CaCO ₃ and Ca(OH) ₂ ha ⁻¹ pH unit ⁻¹	CaCO ₃ 80% kg ha ⁻¹	kg aglime ha ⁻¹	aglime*1 0 (kg ha ⁻¹)	aglime*2 0 (kg ha ⁻¹)	Ca(OH) ₂ 90% kg ha ⁻¹	kg hydrated lime ha ⁻¹	hydr. lime*10 (kg ha ⁻¹)	hydr. lime*20 (kg ha ⁻¹)
		2.90	4,235.32	2,117.66	211.77	264.71	2,647.07	5,294.15	156.71	174.12	1,741.19	3,482.37
		6.85	10,010.75	5,005.38	500.54	625.67	6,256.72	12,513.44	370.40	411.55	4,115.53	8,231.06
		12.12	17,711.33	8,855.67	885.57	1,106.96	11,069.58	22,139.17	655.32	728.13	7,281.33	14,562.65
pH change	Bcap (mmoles H ⁺ kg soil ⁻¹ pH unit ⁻¹)	moles H ⁺ ha ⁻¹	moles S ha ⁻¹ pH unit ⁻¹	S 100% kg ha ⁻¹	S*3 (kg ha ⁻¹)							
	16.08	23,486.77	11,743.39	1,174.34	1,467.92	14,679.23	29,358.46	869.01	965.57	9,655.67	19,311.34	
5.78-5.6	2.37	3,465.26	1,732.63	55.44	166.33							

Table C-6. Soil buffering capacity and amendment application rate calculation table for Lincoln Wheat and Lincoln Potato soil

Lincoln Potato	Column A	Column B	Column C	Column D	Column E	Column F	Column G	Column H	Column I	Column J	Column K	Column L
pH change	Bcap (mmoles OH ⁻ soil ⁻¹ unit ⁻¹)	mmoles OH ⁻ ha ⁻¹	moles CaCO ₃ and Ca(OH) ₂ ha ⁻¹ unit ⁻¹	moles CaCO ₃ and Ca(OH) ₂ ha ⁻¹ pH	CaCO ₃ 80% kg ha ⁻¹	kg aglime ha ⁻¹	aglime*1 0 (kg ha ⁻¹)	aglime*2 0 (kg ha ⁻¹)	Ca(OH) ₂ 90% kg ha ⁻¹	kg hydrated lime ha ⁻¹	hydr. lime*10 (kg ha ⁻¹)	hydr. lime*20 (kg ha ⁻¹)
5.66-6.0	3.58	6,547.29	3,273.64	327.36	409.21	4,092.05	8,184.11	242.25	269.17	2,691.66	5,383.32	
5.66-6.3	6.73	12,324.30	6,162.15	616.22	770.27	7,702.69	15,405.38	456.00	506.67	5,066.66	10,133.32	
5.66-6.7	10.94	20,026.99	10,013.50	1,001.35	1,251.69	12,516.87	25,033.74	741.00	823.33	8,233.32	16,466.64	
5.66-7.0	14.10	25,804.01	12,902.01	1,290.20	1,612.75	16,127.51	32,255.01	954.75	1,060.83	10,608.32	21,216.63	
pH change	Bcap (mmoles H ⁺ unit ⁻¹)	mmoles H ⁺ ha ⁻¹	moles S unit ⁻¹ pH	S 100% kg ha ⁻¹	S*3 (kg ha ⁻¹)							
5.66-5.6	0.63	1,155.40	577.70	18.49	55.46							
Lincoln Wheat	pH change	Bcap (mmoles OH ⁻ soil ⁻¹ unit ⁻¹)	mmoles OH ⁻ ha ⁻¹	moles CaCO ₃ and Ca(OH) ₂ ha ⁻¹ pH	CaCO ₃ 80% kg ha ⁻¹	kg aglime ha ⁻¹	aglime*1 0 (kg ha ⁻¹)	aglime*2 0 (kg ha ⁻¹)	CaCO ₃ 80% kg ha ⁻¹	kg hydrated lime ha ⁻¹	hydr. lime*10 (kg ha ⁻¹)	hydr. lime*20 (kg ha ⁻¹)
5.11-5.6	5.17	9,459.92	4,729.96	473.00	591.24	5,912.45	11,824.89	350.02	388.91	3,889.08	7,778.15	
5.11-6.0	9.39	17,182.30	8,591.15	859.11	1,073.89	10,738.94	21,477.87	635.74	706.38	7,063.83	14,127.67	
5.11-6.3	12.55	22,974.08	11,487.04	1,148.70	1,435.88	14,358.80	28,717.60	850.04	944.49	9,444.90	18,889.80	
5.11-6.7	16.77	30,696.46	15,348.23	1,534.82	1,918.53	19,185.29	38,370.58	1,135.77	1,261.97	12,619.66	25,239.31	
5.11-7.0	19.94	36,488.25	18,244.12	1,824.41	2,280.52	22,805.15	45,610.31	1,350.07	1,500.07	15,000.72	30,001.45	

Calculations:

1 mole $\text{CaCO}_3 = 100 \text{ g}$

1 mole $\text{Ca}(\text{OH})_2 = 74 \text{ g}$

1 mole S = 32 g

Weight of soil/ha = area*depth*bulk density

Column B: Calculation of buffer capacity per pH unit change using equation from buffer curve.

For Pukekawa pH change 6.0-6.3 (e.g.):

$$=(12.1457*6.3-72.4561)-(12.1457*6-72.4561)$$

Column C: =B*soil weight

Column D: =C/2

Column E: =D*100/1000

Column F: =100/80*E

Column G: =F*10

Column H: =F*20

Column I: =D*74/1000

Column J: =100/90*I

Column K: =J*10

Column L: =J*20

Appendix D: Discount rates and factors for CBA purposes, and equations

Table D-1. Discount factors by year for discount rates ranging from 1-10% (Walshe, G. & Daffern, P. (1980). *Managing Cost Benefit Analysis*. London: MacMillan.)

Years	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
1	.9901	.9804	.9709	.9615	.9524	.9434	.9346	.9259	.9174	.9091
2	.9803	.9612	.9426	.9246	.9070	.8900	.8734	.8573	.8417	.8264
3	.9706	.9423	.9151	.8890	.8638	.8396	.8163	.7938	.7722	.7513
4	.9610	.9238	.8885	.8548	.8227	.7921	.7629	.7350	.7084	.6830
5	.9515	.9057	.8626	.8219	.7835	.7473	.7130	.6806	.6499	.6209
6	.9420	.8880	.8375	.7903	.7462	.7050	.6663	.6302	.5963	.5645
7	.9327	.8706	.8131	.7599	.7107	.6651	.6227	.5835	.5470	.5132
8	.9235	.8535	.7894	.7307	.6768	.6274	.5820	.5403	.5019	.4665
9	.9143	.8368	.7664	.7026	.6446	.5919	.5439	.5002	.4604	.4241
10	.9053	.8203	.7441	.6756	.6139	.5584	.5083	.4632	.4224	.3855
11	.8963	.8043	.7224	.6496	.5847	.5268	.4751	.4289	.3875	.3505
12	.8874	.7885	.7014	.6246	.5568	.4970	.4440	.3971	.3555	.3186
13	.8787	.7730	.6810	.6006	.5303	.4688	.4150	.3677	.3262	.2897
14	.8700	.7579	.6611	.5775	.5051	.4423	.3878	.3405	.2992	.2633
15	.8613	.7430	.6419	.5553	.4810	.4173	.3624	.3152	.2745	.2394
16	.8528	.7284	.6232	.5339	.4581	.3936	.3387	.2919	.2519	.2176
17	.8444	.7142	.6050	.5134	.4363	.3714	.3166	.2703	.2311	.1978
18	.8360	.7002	.5874	.4936	.4155	.3503	.2959	.2502	.2120	.1799
19	.8277	.6864	.5703	.4746	.3957	.3305	.2765	.2317	.1945	.1635
20	.8195	.6730	.5537	.4564	.3769	.3118	.2584	.2145	.1784	.1486
21	.8114	.6598	.5375	.4388	.3589	.2942	.2415	.1987	.1637	.1351
22	.8034	.6468	.5219	.4220	.3418	.2775	.2257	.1839	.1502	.1228
23	.7954	.6342	.5067	.4057	.3256	.2618	.2109	.1703	.1378	.1117
24	.7876	.6217	.4919	.3901	.3101	.2470	.1971	.1577	.1264	.1015
25	.7798	.6095	.4776	.3751	.2953	.2330	.1842	.1460	.1160	.0923
26	.7720	.5976	.4637	.3607	.2812	.2198	.1722	.1352	.1064	.0839
27	.7644	.5859	.4502	.3468	.2678	.2074	.1609	.1252	.0976	.0763
28	.7568	.5744	.4371	.3335	.2551	.1956	.1504	.1159	.0895	.0693
29	.7493	.5631	.4243	.3207	.2429	.1846	.1406	.1073	.0822	.0630
30	.7419	.5521	.4120	.3083	.2314	.1741	.1314	.0994	.0754	.0573
31	.7346	.5412	.4000	.2965	.2204	.1643	.1228	.0920	.0691	.0521
32	.7273	.5306	.3883	.2851	.2099	.1550	.1147	.0852	.0634	.0474
33	.7201	.5202	.3770	.2741	.1999	.1462	.1072	.0789	.0582	.0431
34	.7130	.5100	.3660	.2636	.1904	.1379	.1002	.0730	.0534	.0391
35	.7059	.5000	.3554	.2534	.1813	.1301	.0937	.0676	.0490	.0356
36	.6989	.4902	.3450	.2437	.1727	.1227	.0875	.0626	.0449	.0323
37	.6920	.4806	.3350	.2343	.1644	.1158	.0818	.0580	.0412	.0294
38	.6852	.4712	.3252	.2253	.1566	.1092	.0765	.0537	.0378	.0267
39	.6784	.4619	.3158	.2166	.1491	.1031	.0715	.0497	.0347	.0243
40	.6717	.4529	.3066	.2083	.1420	.0972	.0668	.0460	.0318	.0221
41	.6650	.4440	.2976	.2003	.1353	.0917	.0624	.0426	.0292	.0201
42	.6584	.4353	.2890	.1926	.1288	.0865	.0583	.0395	.0268	.0183
43	.6519	.4268	.2805	.1852	.1227	.0816	.0545	.0365	.0246	.0166
44	.6454	.4184	.2724	.1780	.1169	.0770	.0509	.0338	.0226	.0151
45	.6391	.4102	.2644	.1712	.1113	.0727	.0476	.0313	.0207	.0137
46	.6327	.4022	.2567	.1646	.1060	.0685	.0445	.0290	.0190	.0125
47	.6265	.3943	.2493	.1583	.1009	.0647	.0416	.0269	.0174	.0113
48	.6203	.3865	.2420	.1522	.0961	.0610	.0389	.0249	.0160	.0103
49	.6141	.3790	.2350	.1463	.0916	.0575	.0363	.0230	.0147	.0094
50	.6080	.3715	.2281	.1407	.0872	.0543	.0339	.0213	.0134	.0085

Formulae:

Discount factor = D

Discount rate = r

Year = t

P_t = amount paid or received at the end of year t

B_t = benefit received in year t

C_t = cost paid in year t

$$D = \frac{1}{(1 + r)^t}$$

$$PV = \frac{P_t}{(1 + r)^t}$$

$$NPV = \sum_{t=0}^r \frac{B_t - C_t}{(1 + r)^t}$$