Farmers' perceptions of options for pasture remediation and recovery following major tephra fall in New Zealand

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Abstract

Many regions around the world have farms surrounding potentially active volcanoes that have been dormant for decades to centuries. Without any recent experience, a new major eruption and tephra fall would present an unfamiliar soil and pasture remediation challenge. We interviewed 23 farmers from the volcanic North Island of New Zealand in order to gain insight into the current understanding of tephra fall risk and associated production recovery strategies needed for the pastoral agricultural sector. Of the interviewees, 26% had experienced past minor tephra falls on their farms while 70% believed they were at risk of experiencing future tephra fall. Around half of all interviewed farmers (48%), including one who had previously experienced tephra fall, provided suggestions for possible remediation techniques. The remaining half (52%) did not know what to do if tephra were to fall on their farm. The farmer-suggested remediation strategies are: 1) waiting for rainfall to wash away the tephra (for thin falls), 2) cultivation, 3) re-grassing, 4) ploughing, 5) using fertilizers, 6) flipping the upper 0.5 metres of tephra and soil, and 7) physical removal. A key barrier to effective recovery is lack of rapid access to appropriate knowledge during and following a tephra fall. These findings provide potentially useful treatment strategies for heavy tephra fall on pasture and a key reference amongst the farming community when considering farm system preparedness for (and recovery from) tephra fall.

Keywords: *tephra fall, soil remediation, pasture recovery, volcanic eruption, Mt Taranaki, Mt Ruapehu, Taupō, agriculture*

Tephra fall is the most common and widespread volcanic hazard following an explosive eruption. Tephra is the term used for fragmented material ejected from a volcano during a volcanic eruption (Thorarinsson, 1954) and is classified by size into ash (particles less than 2 millimetres), lapilli (2 to 64 mm), and blocks or bombs (more than 64 mm; Gilbert, Lane, Sparks, & Koyaguchi, 1991). Tephra is typically transported by wind in the form of ash clouds and deposited onto the exposed landscape. Tephra fall can damage many sectors of society including critical infrastructure and agricultural systems due to its abrasive, corrosive, and conductive potential (Craig, Wilson, Stewart, Outes et al., 2016; Wilson et al., 2012). Even small amounts of tephra can cause substantial problems, disrupting transportation, water supply, and water treatment systems, and leading to high clean-up costs (Blake, Deligne, Wilson, & Wilson, 2017; Blong, 1984; Cronin, Neall, Lecointre, Hedley, & Loganathan, 2003; Hayes, Wilson, Deligne, Cole, & Hughes, 2017). At greater thicknesses (more than 100 mm), tephra can cause structural damage to buildings, with falls of more than 500 mm often resulting in complete collapse (Blong, 2003; Jenkins et al., 2014; Spence et al., 1996).

Past studies on the effects of tephra on agricultural systems have largely focused on short-term impacts from small eruptions (Bitschene et al., 1993; Cronin et al., 2003; Cronin, Hedley, Neall, & Smith, 1998; Cook, Barron, Papendick, & Williams, 1981; Georgsson & Petursson, 1972; Inbar, Ostera, Parica, Remesal, & Salani, 1995; Johnston, Houghton, Neall, Ronan, & Paton, 2000; Rubin et al., 1994) and long-term recovery following large eruptions (e.g., of Mount Hudson in 1991, Wilson et al., 2012; and of Cordón Caulle in 2011, Craig, Wilson, Stewart, Outes et al., 2016). In the long term (decades to centuries), addition of volcanic material can have positive effects on drainage, aeration, fertility, and water retention of soil (Cook et al., 1981; Nanzyo, Shoji, & Dahlgren, 1993; Warkantin & Maeda, 1980). However, in the short-term, apart from the addition of some beneficial nutrients such as sulphur (Cronin, Hedley, Smith, & Neall, 1997), physical impacts are likely to be negative (Wilson, Cole, Cronin, Stewart, & Johnston, 2011).

Volcanic soils are highly suited for agriculture and horticulture due to their high natural fertility, stability, good drainage characteristics, and high water-holding capacity (Annen & Wagner, 2003; Cronin et al., 1998; Shoji, Dahlgren, & Nanzyo, 1993; Wilson, Cole, Cronin et al., 2011). Past studies have shown that tephra fall can cause considerable immediate impacts on agricultural systems. The 1980 eruption of Mt St Helens, United States of America, resulted in tephra being dispersed across 391,000 square kilometres, burying pastures and crops and resulting in an estimated US$100 million worth of crop losses at the time (Cook et al., 1981; Johansen et al., 1981; Folsom, 1986; Lyons, 1986; Wilson, Cole, Cronin et al., 2011). The eruption of Mt Pinatubo, Philippines, in 1991 dispersed tephra more than 10 mm thick across 7,500 km^2. Over 962 km^2 of this was agricultural land that was seriously affected by tephra fall, with damage to crops, livestock, and fisheries producing a loss of US$86 million (Mercado, 1996; Wilson, Cole, Cronin et al., 2011).

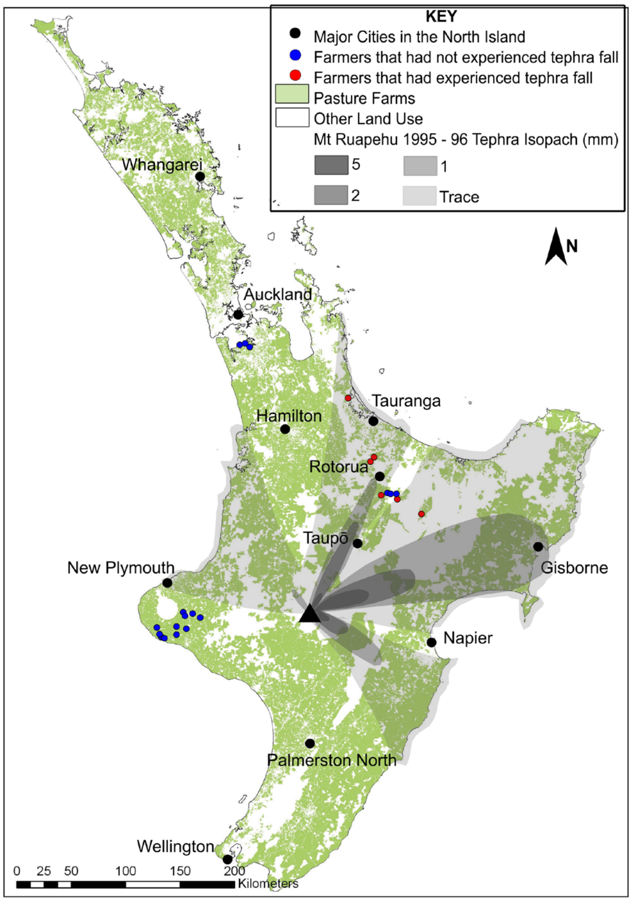

Figure 1. Isopachs in mm of the three largest 1995 and 1996 Ruapehu tephra falls (adapted from Cronin et al., 1998). Red dots show the farm locations of interviewed farmers who reported that they had experienced tephra fall in the past. Land use data from Agribase, (2018). Accessed 14th January 2019 at www.asurequality.com/our-solutions/agribase/.

In New Zealand, tephra falls associated with the 1995/1996 Mt Ruapehu eruption in the North Island covered more than 27,000 km^2 of primary production (Figure 1), causing starvation and fluorosis in thousands of livestock (Cronin et al., 1998). While there has been an increasing focus on documenting the impacts of tephra fall on agricultural systems in the published literature, there has been little focus on recovery strategies, including evaluation of pasture and crop rehabilitation strategies (Neild et al., 1998; Wilson & Cole, 2007; Wilson, Cole, Cronin et al., 2011). Available literature stresses the importance of adapting strategies to the diverse physical and chemical characteristics of tephra falls, the local soil and climatic factors, and the capacities (including knowledge, finance, and technology) of the farmer (Cook et al., 1981; Craig, Wilson, Stewart, Outes et al., 2016; Cronin et al., 1998; Folsom, 1986; Lyons, 1986; Wilson, Cole, Cronin et al., 2011).

Following the 1995/96 Mt Ruapehu eruption sequence, the influence of tephra on agriculture is a key unanswered question. Past studies have largely focused on the impacts of tephra on soil, flora, and fauna health (Craig, 2015). Further, the pastoral agricultural context of New Zealand has changed markedly since the Mt Ruapehu event, with dairying land use increasing by 42.4% between 2002 and 2016, to reach 2.6 million hectares. In 2016, the total area for all agriculture and horticulture use was 45.3% of New Zealand's total land area (12.1 million ha; StatsNZ, n.d.). Intensively farmed pastoral land is common across the soils of both volcanic and sedimentary parent material in New Zealand (Hewitt, Barringer, Forrester, & McNeill, 2010; Figure 1). In the event of large eruptions, such as might be expected from Mt Taranaki, it is estimated that more than 500 farms could be covered with more than 50 mm of tephra (Wilson, Gravley, Leonard, & Rowland, 2009). In this case, farmers would be faced with the difficult task of removing or rehabilitating tephra to return to production.

Tephra fall of less than 20 mm adds beneficial macro and micro-nutrients to the soil as well as influencing pH and adding harmful elements (Ayris & Delmelle 2012). Characteristics such as thickness, density, grain size, and composition of tephra influence the type and extent of impacts caused (Jenkins et al., 2015). Generally a thin (less than 2 mm) coating of tephra can be washed away by rain, while tephra falls of 10 to 100 mm thickness may be remediated over one to five years by cultivation and in some cases may boost pasture growth (Craig, Wilson, Stewart, Villarossa et al., 2016). Cultivation prevents re-mobilization of tephra (e.g., by wind or into waterways) and promotes aeration and bioturbation (where plants or animals rework sediments) to encourage mixing of tephra into the soil (Neild et al., 1998). With thicker tephra falls, more intense remediation is needed to counter its low organic material content, low water holding capacity, low cation-exchange-capacity, and low natural fertility. The options for remediation are similar to cases of flood deposition where thick deposits smother the existing soil and pasture; however, flood silt deposits are generally more fertile, with higher organic content (Hefting et al., 2004; Lockaby, Wheat, & Clawson, 1996).

There have been few historical eruptions with major tephra falls to learn from in New Zealand. Studies on volcanic risk perception in other local communities with past experience of hazardous events are therefore important to consider: an approach also recommended in past work (e.g., Dominey-Howes & Minos-Minopoulos, 2004; Greene, Perry, & Lindell, 1981; Gregg, Houghton, Johnston, Paton, & Swanson, 2004; Lavigne et al., 2008; Murton & Shimabukuro, 1974; Perry, Lindell, & Greene, 1982). A study carried out by Jóhannesdóttir and Gísladóttir (2010) in the village of Vik in southern Iceland revealed that the interviewees were well aware of their volcanic risk, but their lack of mitigation, prevention, and preparedness was due to experiencing no similar hazardous event during their lifetime. According to a study carried out by Bird, Gísladóttir, and Dominey-Howes (2009) in south Iceland, an active response by the public (and farmers) during a volcanic emergency depends not only on their perception of the possible risk, but also their knowledge of preparedness actions.

Several key studies have been carried out on risk perception in New Zealand; these have found that knowledge of a hazard increases with the degree of expected maximum hazard, the degree of damage from prior events, and the amount of information available about the hazard (Johnston, Bebbington, Lai, Houghton, & Paton 1999). Paton, Millar, and Johnston (2001) concluded that, for Mt Ruapehu volcano, the perception of risk typically increases with people's proximity to the volcanic centre, the likelihood of a future disaster, the impact level, and past direct experience of hazards.

We infer from these past studies that farmers in New Zealand may be best able to respond to a volcanic crisis if they have an accurate perception of the risk, have past direct experience of volcanic eruptions, and if they have an understanding of appropriate preparedness and recovery measures. Indeed, the uncommon and complex nature of volcanic hazards necessitates access to expert information by affected communities in order to lead their risk management decisions (Paton, Smith, Daly, & Johnston, 2008).

Here, we present the results of semi-structured interviews with dairy and beef farmers from South Auckland, Bay of Plenty, Rotorua, and Taranaki districts in New Zealand to explore their views and perceptions of volcanic risk, tephra hazard, and possible consequences of tephra fall as well as perceptions of possible remediation techniques for recovering pastures and soils following tephra fall. As far as we are aware, this paper presents the first account of farmers' views on remediation of tephra-affected pastures and soils. The farmers' insights may guide future work on building farmer resilience and provide a basis for future field and laboratory testing of possible rehabilitation techniques.

Tephra Hazard in New Zealand

It has been estimated that about 25% of the world's historical and prehistorical eruptions with a volcanic explosivity index (VEI) of five or more were from the Central North Island of New Zealand. This region contains the world's highest concentration of youthful rhyolite volcanoes (Simkin & Siebert, 1994; see Figure 2). In the central North Island, andesitic volcanism started circa two million years ago and was joined by voluminous rhyolitic (plus minor basaltic and dacitic) activity from at least circa 1.6 million years ago (Wilson et al., 1995). Brief characteristics of different types of magma are given in Appendix 1 and a brief summary of past volcanic activity in New Zealand is given below.

The Taupō Volcanic Zone of New Zealand contains both andesitic stratovolcanoes (e.g., Mt Ruapehu and Mt Tongariro), built by comparatively frequent small eruptions, and predominantly rhyolitic calderas (e.g., Okataina and Taupō volcanic centres), which can produce much larger eruptions at longer intervals (Cole 1979; Wilson et al., 1984). There have been numerous recent and historical tephra-generating eruptions from the Taupō Volcanic Zone. Widespread tephra layers preserved in sedimentary records on the ring plain to the east of Mt Ruapehu reveal that this stratovolcano

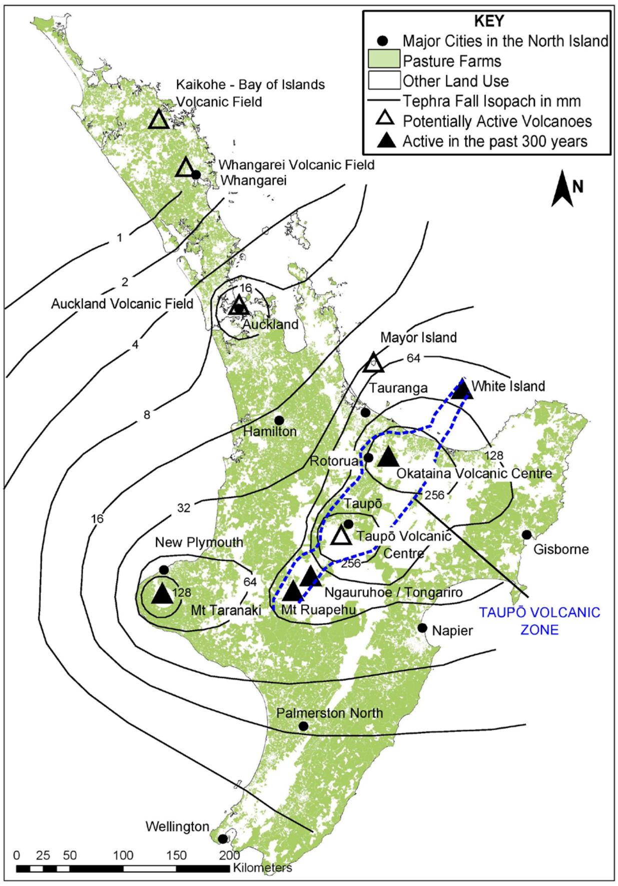

Figure 2. Tephra hazard map with tephra thickness in mm for a 10,000-year return period for all significant volcanic sources (adapted from Hurst & Smith 2010). Locations of potentially active volcanoes along with major towns in New Zealand's North Island are also shown. Land use data from Agribase (2018). Accessed 14th January 2019 at www.asurequality.com/our-solutions/agribase/.

has produced a total of 19 major eruptions, interspersed with smaller events, over the past circa 1,800 years (Moebis, Cronin, Neall, & Smith, 2011). The most recent eruption from Mt Ruapehu took place as a series of events between September 1995 and August 1996 (Cronin et al., 2003; Johnston et al., 2000; Newnham, Dirks, & Samaranayake, 2010). A large eruption on June 17, 1996 dispersed large amounts of volcanic tephra over a wide area reaching more than 300 km to the north and east of Mt Ruapehu (Figure 1). The eruption column reached an estimated 7 - 10 km, with the axis of tephra dispersal sweeping westwards across the central North Island as the wind direction shifted from SW to SE (Cronin et al., 2003). An estimated 7 million tons of tephra were dispersed, with light tephra falls over the nearby cities of Taupō and Rotorua (Cronin et al., 1998; Figure 1).

The adjacent Mt Tongariro of the Tongariro Volcanic Zone erupted suddenly at 2350 hours NZST on 6th August 2012 after being inactive for 115 years. The eruption occurred from the upper Te Maari Crater on the volcano's northern flanks, which was previously active in 1869, 1892, and 1896 - 1897 (Cronin et al., 2014). These past eruptions were short Vulcanian and phreatic explosions, releasing tephra plumes with wet surges and lahars; the approximately 400,000 cubic metres of tephra generated during the 2012 event was dispersed over a vast area (Cronin et. al., 2014).

The largest historical eruption from the Taupō Volcanic Zone was a basaltic Plinian eruption from Mt Tarawera and nearby Lake Rotomahana of the Okataina Volcanic Centre, in the early hours of 10 June, 1886 (Keam, 2016). The eruption started from the preexisting Tarawera rhyolite dome, producing a tephra column with a height estimated at 28 km (Walker, Self, & Wilson, 1984), and then extended into Lake Rotomahana. The eruption from this latter area was much more violent due to the interaction of water and deposited a thick layer of Rotomahana mud on surrounding areas. The whole eruption of about 2 km^3 lasted only a few hours during the morning of 10 June, 1886 (Keam, 2016). One of the most productive caldera systems in the world is the Taupō volcanic centre (Figure 2). The latest eruption from Taupō was in 232 ± 5 AD (Hogg, Lowe, Palmer, Boswijk, & Ramsey, 2012) and ejected 35 km^3 of magma (Potter, Scott, Jolly, Johnston, & Neall, 2015).

Mt Taranaki, a 2,518 metre high andesitic stratovolcano situated in the Taranaki region (Figure 2), has erupted over 220 times in the last 30,000 years (Damaschke, Cronin, Holt, Bebbington, & Hogg, 2017), spreading tephra over the surrounding areas and as far north as the city of Auckland (about 270 km away; Sandiford, Alloway, & Shane, 2001; Shane 2005). Mt Taranaki is located in the middle of an economically significant region of New Zealand, which contributes 10% of the country's total dairy land (Ballingall & Pambudi, 2017). According to the best currently available model for Mt Taranaki, it is estimated that there is a 33 – 42% chance of an eruption occurring within the next 50 years (Damaschke et al., 2017).

The basaltic Auckland Volcanic Field (AVF) has been active over the last circa 200,000 years and consists of 53 monogenetic (only erupting once) eruptive centres (Leonard et al., 2017). Lava flows and tephra falls are the most widespread deposits of the AVF (Kereszturi et al., 2014). Although there have been no historical eruptions from the AVF (i.e., since written records began), the most recent eruption, forming Rangitoto island about

600 years ago, was witnessed by early Māori. Future eruptions from the AVF are likely to be smaller than those from New Zealand's andesitic and rhyolite centres further south.

A Probabilistic Volcanic Hazard Model (PVHM) developed for New Zealand by Hurst and Smith (2010) estimates the likelihood of tephra deposits of any given thickness at any site, based on the frequency-magnitude relations of all significant volcanic sources and wind distribution statistics. They found that a typical 10,000-year period could result in the deposition of up to 300 mm of tephra in many central North Island locations (Figure 2).

The magnitude of possible eruptions that could affect agriculture in New Zealand ranges from minor andesitic events such as the 1995/1996 Mt Ruapehu eruptions, up to a major rhyolitic Plinian event, such as the 232 AD Taupō eruption (Wilson et al., 1995), which would eliminate agriculture in the central North Island for an extended time period. Mt Taranaki produces many events with typically low volume; however Torres-Orozco, Cronin, Pardo, and Palmer (2018) report a Plinian eruption every 300 years on average over the past 5,000 years.

Although New Zealand has a comprehensive monitoring network[1] and warning system for future eruptions, there are few mitigation measures for impacts to pasture under rapid accumulation of heavy tephra fall. During volcanic unrest periods, GNS Science release tephra fall prediction maps with their Volcanic Alert Bulletins. These show the likely tephra fall location and thickness for that particular day, given the current weather patterns, thus providing very short notice to farmers in the tephra hazard zone. If more time were available (e.g., months to years) possible preparatory measures could be taken, such as de-stocking or moving livestock. The cost of stock evacuation is exceptionally high (Wilson, Dantas, & Cole, 2009) and thus such a warning would likely need to have a high degree of certainty for the measures to be economically viable. This degree of certainty is highly unlikely with current technology and understanding of volcanoes. Far more likely is that only a few days to hours of warning will be possible, and so little can be done other than to evacuate livestock. Post-tephra fall remediation and pasture recovery thus becomes a key recovery consideration.

1 https://www.geonet.org.nz/volcano/

Method

Semi-structured Interviews

Our study used semi-structured interviews, a widely used method of data collection within the social sciences (Bradford & Cullen, 2013). Such interviews are valuable because they allow researchers to explore subjective viewpoints (Flick, 2009) and to gather in-depth accounts of people's experiences. Typically, an interview schedule is used, which enables the researcher to address a defined topic while allowing the respondent to answer in his or her own terms and to discuss issues and topics pertinent to them (Choak, 2013). In this sense, the interview should resemble a flowing conversation (Rubin & Rubin 2011; Choak, 2013). The methodological components of the interview were approved by the University of Auckland human participation ethics committee (Reference number: 016940).

In this study, 23 farmers from South Auckland, Bay of Plenty, Rotorua, and Taranaki districts were interviewed. The regions were selected due to their susceptibility to tephra fall from Taupō Volcanic Zone and Taranaki volcanoes (Figures 1 and 2). According to the PVHM model developed by Hurst and Smith (2010) for New Zealand, 10,000-year return period eruptions are capable of depositing up to 300 mm thick tephra falls over most of the central North Island. The participants themselves were selected by snowball sampling with the help of Dairy NZ (an industry research organization) and the Taranaki Regional Council. Dairy NZ has regular meetings with their farmer groups; we were invited to attend a meeting at Karaka in the Auckland region on July 5th, 2016, where a brief introduction to the study was given to the farmers present. This encouraged the immediate participation of two farmers. Dairy NZ subsequently wrote to their farmer groups seeking participants for the study, which resulted in two more farmer participants; these two farmers then spread the word about the research within their network, resulting in a further eight farmer participants. The Taranaki Regional Council assisted by spreading the word about this study amongst farmers in their region; those interested in participating then gave their contact details to the council and were subsequently contacted by the researchers to arrange the interview.

A participant information sheet and consent form were signed by all interviewed farmers before the interview and participants were informed that they could withdraw from the study at any point. Eleven farmers were interviewed face-to-face and 12 over the phone, with every interview voice recorded. The interviews were carried out between July and November 2016, with each interview lasting between 20 minutes to 1 hour. The farmers' answers were recorded in an Excel spreadsheet under the appropriate headings and analysed semi-quantitatively. The interview questions consisted of a few closed and mostly open-ended questions that can be summarized and grouped into the following three areas (see Appendix 2 for the full list of questions).

General farmer profile. The first group of questions obtained general information from the farmer and solicited information such as when they started their farming career, whether they were first generation farmers, how many hectares they farmed, what kind of farming they practiced (dairy of beef), what kind of pasture mix they grew on their farm, whether they had tried growing any other crop on their farm, and which crop had been most consistent in terms of making a profit. Farmers were also asked how their farming style had evolved during their time farming, what important changes they had implemented or encountered on their farm, and how these changes affected productivity and profitability. They were also asked if their farm had experienced any natural hazard events other than volcanic tephra fall (e.g., flood, landslide, earthquake, snow, drought).

Farmer experiences and perceptions of tephra fall hazard. The second group of questions were based on farmers' past encounters with tephra fall on their farm, if any. They were asked if they had experienced tephra fall and if so, when. They were also asked if they considered their farm at risk of receiving heavy tephra fall and what other types of hazards might be associated with a volcanic eruption.

Farmer thoughts on strategies to combat tephra fall effects. The third group of questions was designed to explore farmers' thoughts on techniques for remediating tephra-affected soils. All farmers were asked to speculate what they thought could be done if they were faced with light tephra fall (0 to 10 mm in thickness) and medium to heavy tephra fall (10 to 300 mm in thickness) covering their pasture. If they had experienced any natural hazard events other than tephra fall (e.g., flood, drought) or soil damage or poor fertility, they were asked how they recovered from the resulting effects.

Results

General Farmer Profile

Of the 23 farmers interviewed, 21 were dairy farmers and two were dairy and beef farmers. The majority of farmers were highly experienced in dairy farming, with the most experienced farmer having 58 years' experience and the least experienced 7 years. The farms ranged in size from 60 ha to 640 ha. The livestock count per farmer ranged from 170 to 1,825 dairy cows. All farm production systems were centered on growing pasture for either direct livestock consumption or to make supplementary feed, which can then be fed to livestock during low pasture growth periods (e.g., winter) or high-energy demand periods (e.g., calving and milking). The majority of the interviewed farmers used a ryegrass (*lolium multiflorum*) and clover (*trifolium repens*) mix as their dominant pasture type, with two farmers growing chicory (*cichorium intybus*), plantain (*plantago lanceolate*), and lucerne (*medicago sativa*) as supplementary feed along with ryegrass and clover mix. Seventeen farmers had experienced the effects of non-volcanic natural hazards on their farm; in order of most-to-least experienced hazard (number of affected farmers in parentheses): drought (10), floods (4), wind/storm/cyclone (4), snow/pugging (3), earthquake/heavy rainfall (2), and landslide/infertile soil/coastal erosion (1). See Supplementary file 1.

Farmer Experiences and Perceptions of Tephra Fall Hazard

Of the 23 farmers who were interviewed, only six (five dairy and one dairy and beef farmer, all from the Bay of Plenty region) had experienced tephra fall on their farms during the 1995/96 eruption of Mt Ruapehu (Figure 1). These six farmers reported receiving tephra in various thicknesses, including less than 1 mm, a "very light dusting" (two farmers), 10 mm, 15 – 25 mm, and a "quite reasonable" amount.

Sixteen of the farmers (around 70%) stated that heavy tephra fall is a possible threat to their farms, while six (26%) believed that they were free from this hazard, and one was unsure (see Figure 3). The 16 farmers who agreed their farms were at risk of heavy tephra fall included five who had already experienced tephra fall on their farm. Interestingly, the remaining farmer who had already experienced tephra fall on their farm believed this was a rare, once in a lifetime situation. We acknowledge that the expected frequency of thin tephra falls in the North Island of New Zealand is much

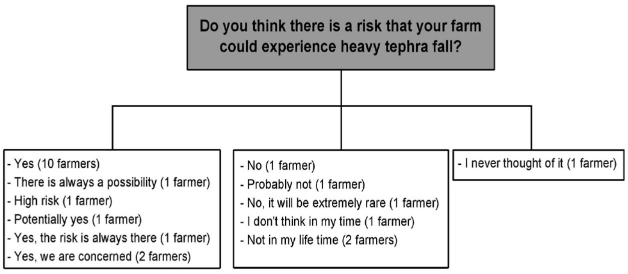

Figure 3. Schematic illustration of farmer responses to the question: "Do you think there is a risk that your farm could experience heavy tephra fall?"

greater than for thick tephra falls. Nine of the 16 farmers who considered their farm at risk of heavy tephra fall described additional possible volcanic hazards and impacts (see Figure 4).

Farmer Thoughts on Strategies to Combat Tephra Fall Effects

The six farmers who experienced the 1995/96 Mt Ruapehu eruption did not notice any adverse effects on the soil or on their farm and waited for rainfall to wash the tephra coat from the pasture. Around half of all interviewed farmers (11; 48%), including one who had previously experienced tephra fall, provided suggestions for possible remediation techniques. The remaining half (12; 52%) did not know what to do if tephra were to fall on their farm. Of the 16 farmers who identified heavy tephra fall as a risk to their farm, nine were able to suggest possible remediation measures. Overall, the following possible remediation techniques were suggested (with the number of farmers mentioning the technique in parentheses).

Rainfall/Irrigation (9 farmers): In the event of light tephra fall, participants suggested that they would wait

	Farmer								
	1	2	3	4	5	6	7	8	9
Volcanic Hazards									
Pyroclastic flows	✓								
Tephra fall	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lava flows			✓			✓		✓	
Lahars		✓				✓			✓
Possible Impacts									
Damage to infrastructure				✓					
Rise in atmospheric temp.					✓				
Pollution of waterways					✓				
Disruption of electricity							✓		
Disruption of water supply							✓	✓	
Disruption of transportation							✓		
Threat to livestock							✓		
Disruption of feed transport				✓					

Figure 4. Volcanic hazards and possible impacts identified by the nine farmers who also considered their farm at risk of heavy tephra fall.

for rainfall to wash tephra from pasture. In this case, the farmers anticipate that the grass and soil would return to their original conditions and could continue to be used as before. Depending on the season, participants also considered irrigating the tephra-affected soil as a recovery option. Irrigation would also have the effect of washing away much of the tephra settled on the pasture.

Using fertilizers (2 farmers): Two farmers recognized that tephra fall could cause an imbalance of soil nutrients and suggested that this could be remediated by targeted fertilizer mixtures.

Cultivation/Re-grassing (8 farmers): In the event of thick tephra fall, farmers thought that re-grassing or cultivating the affected paddock would be useful. In this method the whole paddock would be sprayed with herbicide (if needed), followed by tilling to produce a good seed bed.

Ploughing (3 farmers): For medium to thick tephra fall, farmers recommended ploughing as a possible recovery technique. It was suggested that ploughing 6 to 10 inches (approximately 10 to 15 cm) below the top-soil and mixing the tephra with soil would reduce the toxicity of tephra and reduce its impacts.

Machine removal (3 farmers): Three of the farmers thought that, in the case of heavy tephra fall conditions (where tephra forms a thick coat over the pasture soils), excavating or grading the tephra using heavy machinery would be the only option left to recover the pasture.

Flipping (1 farmer): One participant, from the Bay of Plenty, practised flipping on his farm in order to bring back to the surface the buried layers that were once fertile top soils prior to the 232 ± 5 AD Taupō eruption (Hogg et al., 2012). This reportedly gave excellent pasture growth and soil fertility results. Flipping is a method where a large excavator is used to invert the soil profile, bringing the 1 to 1.5 m deep sub-soil to the top. The dairy farmer who practised flipping gained an increase of 40% dry matter over his normal soil. The farmer suggested that flipping could be an ideal remediation strategy for heavy tephra fall.

Farmers also suggested a few remediation strategies that they had used, or were aware of, to recover soils following other adverse natural events, suggesting these may also be useful in the remediation of tephra affected soils.

Organic fertilizer/Cow-shed effluent/Chicken manure (13 farmers): Over half of the farmers interviewed sprayed their cow-shed washings onto paddocks, which helps enhance pasture growth, increases organic nutrients in the soil, and also increases the number and growth of worms in soil. They stated that this method can be utilised to increase organic nutrient levels in the soil, which is likely to drop even after light tephra fall.

Liming (9 farmers): Over a third of interviewed farmers practised liming on their farm to maintain the pH of soil to enhance grass growth. Their comments suggested that considering the acidic nature of tephra, liming could be an appropriate recovery method following tephra fall.

Different grass mix (2 farmers): Farmers suggested that using a different grass mix would be useful in order to recover light tephra-affected soil. It was suggested that a mix of ryegrass, clover, and chicory gave good results with respect to pasture growth. The farmers used this technique to overcome the damage caused by pugging and heavy rainfall. They perceived that using different grass mix on tephra can be useful as different grass types can vary in their tolerance to soil conditions.

It is also worth noting that several farmers mentioned other response strategies such as de-stocking the farm and/or providing external or supplementary feed (Supplementary file 1). These suggestions highlighted that pasture rehabilitation must be considered in the wider context of the recovery of the farming system as a whole.

Discussion

Extreme natural hazard events such as flooding, landslides, or deposition of volcanic material such as tephra fall may completely disturb or bury soils. In cases of extreme volcanic deposition, farmers must abandon the land (Wilson, Gravely et al., 2009). There are several global examples where thick volcanic tephra fall has forced temporary abandonment of farms, including eruptions at Hekla volcano, Iceland (Thorarinsson 1979), and Vulcan Hudson, Chile (Bitschene et al. 1993; Scasso, Corbella, & Tiberi, 1994). In other situations, physical or biological remediation of the new tephra-covered soils may be possible.

Following the 1943 to 1956 eruption of Volcán de Parícutin, Mexico, farmers discovered that they could recover production by cultivating tephra into the underlying soil (Luhr, Simkin, & Cuasay, 1993; Ort et al., 2008; Rees & Grayson, 1979). Following the 1991 eruption of Vulcan Hudson in Chile, over 1 m of tephra was deposited around 20 to 40 km from the volcano (Wilson, Cole, Stewart, Cronin, & Johnston, 2011). The farmers in this area tried different remediation strategies to recover pastures, such as applying fertilizers and sowing different types of grasses including indigenous and foreign ryegrasses and red and white clovers. While the grass had moderate success, adding fertilizer alone did not help due to rapid leaching (Wilson, Cole, Cronin et al., 2011). Other farmers in the area spread hay over the tephra to increase the organic content of the soil, which helped but was expensive (Wilson, Cole, Cronin et al., 2011). Areas with light tephra fall (10 mm) were able to be rehabilitated rapidly by just irrigation (Wilson, Cole, Cronin et al., 2011). Areas further away from the volcano received 200 to 300 mm of tephra, which was ploughed using tractor-mounted ploughs or rotary hoes. Other farmers tilled the thick tephra deposits into the soil using rakes and shovels, which was effective and led to higher yields within two to three years (Wilson, Cole, Cronin et al., 2011). It is clear from past experience around the world that remediation strategies need to be designed based on the individual context, taking into consideration factors such as farming system, climate, soil type, farm topography, tephra chemistry, thickness and grain size, and availability of fertilizers, labour, and machinery. This array of possible contexts means that tailoring remediation measures to specific events may be challenging. This study attempts to fill this gap by shedding light on farmer perceptions of potentially useful treatment strategies for heavy tephra fall on pasture in the New Zealand context.

Farmers' Perceptions of Tephra Fall Hazard

Sixteen of the 23 interviewed farmers (nearly 70%) considered heavy tephra fall as a possible threat in the future, yet only nine of these suggested potential mitigation strategies. Participants recognized the rarity of these events, noting none in the past 50 years. Farmers that experienced tephra fall had only experienced minor falls, which contributes to their overall perception of volcanic risk being low. This concurs with past work which has found that knowledge of a hazard is directly related to the proximity of the hazard source, degree of expected maximum hazard, the degree of damage, experience of prior events, and information available (Johnston et al., 1999; Paton et al., 2001).

Interestingly, the farmers who experienced tephra fall on their farms from the Mt Ruapehu 1995/1996 eruption perceived a range of tephra thicknesses from less than

1 mm to 15 to 25 mm, despite being located in the areas thought to have received trace amounts of tephra from this eruption (Figure 1). We believe this represents an over-reporting of tephra thickness by lay people, which was noted during this and other past eruptions in New Zealand.

Over half (12; 52%) of the farmers were unable to suggest remediation strategies and most had given the topic little thought. This may relate to a lack of past experience of volcanic eruptions coupled with a sense of not being vulnerable to this hazard. A sense of vulnerability encourages response to warnings and implementation of preventative measures (Johnston et al., 1999). Limón-Hernández et al. (2009) found communities at El Chichón volcano in Mexico needed a comprehensive educational programme long before an eruption to be prepared. This type of education would also be important for New Zealand farmers that may face major tephra falls in the future.

Farmer-suggested Remediation Techniques

Our survey results show that farmers acknowledged the importance of knowing effective tephra remediation strategies for pasture soils. Farmers suggested some conventional methods of remediation, such as cultivation, re-grassing, ploughing, and using fertilizer mix. One of the farmers suggested an unconventional method, potentially also the most expensive: namely, to excavate and invert (flip) the soil to expose the sub-soil. Below we discuss these strategies in the context of past work and provide a summary in Figure 5.

Six farmers who had experienced light tephra fall on their farm during the 1995/96 Mt Ruapehu eruption waited for rainfall to wash away the tephra. This also occurred in distal areas after the 1991 Vulcan Hudson eruption (Wilson, Cole, Cronin et al., 2011). In many small eruptions, this would be the only action needed, but it implies that supplementary feed is required during the waiting period.

Two farmers suggested applying fertilizers could speed up remediation, but we note that this was not effective when applied in the Upper Ibáñez valley after the 1991 eruption of Vulcan Hudson (Wilson, Cole, Cronin et al., 2011). However, different fertilizer and liming treatments have proven to be useful in boosting post-eruptive growth in the New Zealand context (Cronin et al., 1997).

Nearly 35% of participants supported cultivation/re-grassing to recover pasture soils following heavy tephra fall; this was effective at Volcán de Parícutin, Mexico (Luhr et al., 1993; Ort et al., 2008; Rees & Grayson, 1979), and in Chile and Argentina following eruptions (Wilson, Cole, Cronin et al., 2011). This also had the benefit of helping to stabilize the tephra from further redistribution (e.g., by wind or water). Ploughing heavy tephra-covered soil was suggested by our participants for heavy tephra fall and was also effective at Chile Chico, Los Antiguos, and Perito Moreno following the 1991 Hudson eruption (Wilson, Cole, Cronin et al., 2011). In practice, cultivation and ploughing can be considered a similar process: namely mixing the tephra with the soil in preparation for sowing of seeds. Treating these collectively, 11 (48%) farmers recommended this strategy. Indeed, such tilling of tephra into the upper soil horizon has proven to speed up recovery and pasture re-establishment (Craig, Wilson, Stewart, Villarossa et al., 2016).

Tephra thickness	Remediation strategy	Benefits
Light tephra fall (0 – 10 mm)	Rainfall / Irrigation*	Will help to wash away tephra (Wilson, Cole, Cronin et al., 2011)
	Organic fertilizer (cow shed effluent; chicken manure)	Will increase organic content (Wilson, Cole, Cronin et al., 2011); may not be available in large quantities if de-stocking has occurred
	Fertilizer	Supplies nutrients for pasture growth (Wilson, Cole, Cronin et al., 2011)
	Liming	May help increase the tephra pH levels as tephra is typically acidic
	Different grass mix*#	Some grasses may have higher tolerance toward tephra (Wilson, Cole, Cronin et al., 2011)
Medium to Heavy tephra fall (10 – 300 mm)	Cultivation*	Helps break the tephra layer and bring the buried soil to the top (Wilson, Cole, Cronin et al., 2011; Craig, Wilson, Stewart, Villarossa et al., 2016)
	Ploughing*	Helps mix tephra and underlying soil (Wilson, Cole, Cronin et al., 2011)
	Removal using heavy machinery*	Helps get rid of thick tephra layers (Wilson, Cole, Cronin et al., 2011)
	Flipping	Will bring sub-soils to the top and bury tephra

Figure 5. Remediation strategies that could be implemented for light and medium to heavy tephra fall based on farmer suggestions and literature review.
* = remediation strategies suggested by farmers that have shown success overseas according to the literature review.
# = has shown success for medium to heavy tephra fall overseas.

Removing thick tephra using heavy machinery was suggested by three of the farmers; this approach was also taken following the Hudson eruption where graders were used to scrape and remove the tephra (Wilson, Cole, Stewart et al., 2011). Excavation is one of the oldest remediation methods for contaminated soil (Lambert, Leven, & Green, 2000) and may be useful on smaller farms or for high-value crops. However, the average farm area amongst the interviewed farmers was 250 ha, thus removing the thick tephra from such large areas would be impractical and expensive. The advantage of this method is the complete removal of the contaminants (Wood, 1997), but the disadvantages include disposing of the removed tephra and the feasibility of this technique on many of New Zealand's rugged landscapes.

Thirteen farmers (57%) reported using organic fertilizers/manure/cow-shed effluent on their farms to recover soils degraded due to other causes such as pugging, floods, droughts, or erosion. Lal, Griffin, Apt, Lave, and Morgan (2004) reported that adding crop residues (green manure) into the soils not only increases the carbon content but also improves the soil structure. In the Upper Ibáñez valley, Vulcan Hudson, hay was used to increase the organic content of the tephra-affected soils, but it was expensive and only used in places where tephra was too thick to be cultivated (Wilson, Cole, Cronin et al., 2011). Hay is therefore unlikely to be a practical solution on large New Zealand farms. It is important to know how tephra would react to low-cost organic manure such as cow-shed effluent, which is readily available on most dairy farms. Another option might be chicken manure, a strategy suggested by one farmer for improving infertile soils (See Supplementary file 1). Any remediation strategy using effluent would be challenging on a large farm and may require imported effluent as well as additional machinery.

Two of the interviewed farmers suggested using different and hardier grass mixes to speed recovery. This showed success following thick tephra falls (more than 500 mm) from the 1991 Vulcan Hudson eruption, especially the indigenous grasses and a variety of foreign ryegrasses and red and white clovers (Wilson, Cole, Cronin et al., 2011). This is similar to a basic form of phytoremediation, which is often used to stabilize mine tailings and prevent leaching of pollutants (Fellet, Marchiol, Delle Vedove, & Peressotti, 2011). This may need to be carried out in conjunction with other remediation methods such as cultivation and fertilization in order for the pasture to establish.

Conclusions and Recommendations

New Zealand, especially the middle portions of the North Island, is at risk from heavy tephra fall, with many volcanoes capable of producing tephra fall more than 100 mm thick on pastures. It is important for the New Zealand agricultural sector to have a clear understanding of possible ways to recover from this volcanic hazard, prior to an eruption. There are only a few studies of rehabilitation of pasture following thick tephra falls in the literature, and none of these are from New Zealand. It is therefore equally important to investigate potentially useful local options. Although our study used a small sample which limits the generalizability and strength of conclusions, our findings usefully illuminate farmers' perceptions of tephra fall hazard and present insight into their experiences and thoughts on effective rehabilitation methods. We have prepared a preliminary guide to possible rehabilitation strategies for tephra-affected pasture based on the results of our study together with information from the literature (see Figure 5). Some of the strategies have only been suggested by farmers and it is unclear whether they will indeed work. On the other hand, many of the recovery strategies suggested by farmers have proven effective in other parts of the world. We thus provide preliminary insights and recommend further research to test these suggested remediation techniques on New Zealand pasture soils under simulated heavy tephra fall. While we acknowledge that pasture remediation is just one aspect of farming system recovery following a volcanic eruption, we believe our study has the potential to raise awareness amongst the farming community of tephra fall hazard and to prompt the development of possible preparedness strategies for the farming system as a whole.

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Appendices

Appendix 1: Characteristics of magmas

Typical characteristics (silica content, viscosity, gas content, eruption style, landforms, and hazards) of basalt, andesite, and rhyolite magmas. PDC stands for pyroclastic density current (Lindsay, Thompson, Shane, 2016).

Magma Type	Silica content	Viscosity	Gas content	Eruption style	Landforms	Typical hazards
Basalt	Low (45 – 55%)	Low (flows easily)	Typically low	Typically effusive	Shield volcano, scoria cone, lava field, maar	Lava flow, PDC (base surge), ballistics, tephra fall
Andesite	Intermediate (55 – 63%)	Intermediate (resistant to flow)	Typically intermediate	Typically explosive	Stratovolcano	Lava flow, PDC, lahar, ballistics, tephra fall, debris, avalanche
Rhyolite	High (>70%)	High (extremely resistant to flow)	Typically high (4 – 6%)	Very explosive	Lava dome, caldera	PDC, lahar, ballistics, tephra fall

Appendix 2: Interview questions (Initial interviews)

1) When did you start farming?
2) Are you a first generation farm owner or has your family been in farming in the past?
3) How many hectares is this farm?
4) What kind of farming is practised in your farm?
5) What pasture species/mixtures do you grow? Have you tried growing any other forage crops or pasture mixes?
6) What has been your most consistent crop in terms of making a good profit?
7) What is the livestock count of your farm?
8) Has your farm been affected by any volcanic activity since you began farming there?
9) Have you ever encountered any volcanic ashfall on your farm?
10) Do you think there is a risk that your farm could experience heavy tephra fall?
11) What do you think that are the potential risks of the nearest volcano on your farm?
12) What would you do if your farm received 1mm, 100mm or >300mm of ashfall?
13) Have you ever faced any major disturbance in the soil fertility of your farm?
14) Have you ever faced serious infertility / erosion / landslide / flooding / drought in your farm soil? How serious was it?
15) Have you encountered any other natural disaster on your farm?
16) What are the remediation or recovery practices practised by you in order to repair the infertile/un-productive/ damaged soil?
17) Have you faced any threat to your livestock due to the nearest volcano or any other natural phenomenon (e.g. weather, flood, drought etc)?
18) What was the biggest change you encountered during your years farming?
19) What would you say have been the biggest changes you've implemented on your own farm since you've been farming here? Do they correspond with what you think the biggest changes have been in the industry during that time?
20) Have you seen a change in your land since you first started farming?
21) Are there any differences between your farm now and your farm when you had started farming?