Understanding warming effects on vegetation through geothermal hotspots: A case study of the Wairakei - Tauhara geothermal field, Taupo, New Zealand

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Abstract

Understanding and predicting warming effects on vegetation is a key challenge of the 21st century. To date, warming experiments have been limited to isolated laboratory studies, which have been criticised as too small-scale and overly simplistic because they were not conducted in a natural context. As such, understanding the future consequence of warming using a natural environment and across an effective timeframe has become a key goal of vegetation dynamic studies. Warming experiments in undisturbed settings are particularly important for understanding the complex responses of vegetation to warming within a multifunctional ecosystem. Furthermore, a natural setting approach can include other variables that will improve the current understanding of the effects of warming on vegetation.

Through the course of this thesis, I developed a warming experiment to utilise natural thermal gradients in a geothermal ecosystem spanning a wide range of soil temperatures from 18 - 56 °C. First, I used historical aerial photographs from 1975 to 2016 to review the change in vegetation distribution around geothermal surface features, correlating the change with thermal infrared images captured in 2009 and 2014. This review revealed that as the geothermal features cool, vegetation growth and development is enhanced. Thus, examining the response of vegetation to changes in thermal gradients provided a means of simulating warming. Second, I used an unmanned aerial vehicle (UAV) to capture thermal infrared and standard colour imagery to address the knowledge gap in remote sensing data. I demonstrated the use of a small, cost effective UAV and highlighted techniques in sampling, processing and analysing images captured by UAV.

Third, after investigating the historical response of vegetation to geothermal features, I set up a field experiment to investigate vegetation regeneration and root biomass responses to the soil temperature gradients and other geothermally associated conditions

(soil chemistry). I found that although other conditions did limit vegetation establishment and growth, the thermal gradient had the most dominant effect.

Given the important role that vegetation plays in the ecosystem, it is vital to understand any unpredictable changes and then to apply appropriate actions within an appropriate timeframe. This thesis addresses a critical gap in experimental soil warming, making use of a geothermal system. Warming experiments within geothermal gradients demonstrate how small-scale experiments can be used to inform future vegetation responses to warming. Using the geothermal system as the natural setting for a warming experiment also provides the opportunity to replicate similar studies around the world to improve our understanding of local area vegetation dynamics.

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Attestation of authorship

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

Abdul Nishar

Date: 31/01/2017

Co-authored works

Chapters 3-5 of this thesis represent three separate studies that have been submitted to peer-reviewed journals for consideration for publication. All co-authors have approved the inclusion of the joint work in this doctoral thesis.

Study 1

Review the responses of vegetation to temperature gradients around geothermal features (Chapter 3 in thesis).

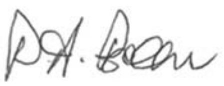
Contribution: Abdul Nishar conceived the idea, collected and analysed data, and wrote the manuscript (87% contribution). Dan Breen contributed to writing the manuscript (10%). Grant Lawrence assisted with testing the methodology, reviewed and provided feedback on the manuscript (2%). Barbara Bollard Breen reviewed and provided feedback on the manuscript (1%).

Dr. Dan Breen | Grant Lawrence | Assoc. Prof. Barbara Bollard Breen

Study 2

Thermal infrared imaging of geothermal environments and by an unmanned aerial vehicle (UAV) (Chapter 4 in thesis).

Contribution: Abdul Nishar conceived the idea, carried out the fieldwork and analysed data, and wrote the manuscript (83% contribution). Dan Breen contributed to writing the manuscript (10%). Steve Richards assisted with the methodology, reviewed and provided feedback on the manuscript (5%). Barbara Bollard Breen and John Robertson both reviewed and provided feedback on the manuscript (1% each).

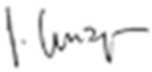
Dr. Dan Breen Steve Richards Assoc. Prof. Barbara Bollard Breen

Dr. John Robertson

Study 3

Temperature effects on biomass and vegetation regeneration from a geothermally heated soil system (Chapter 5 in thesis).

Contribution: Abdul Nishar co-conceived the idea, carried out the fieldwork and analysed data, and wrote the manuscript (80% contribution). Martin Bader assisted with data analysis and contributed to writing the manuscript (10%). Sebastian Leuzinger co-conceived the idea, reviewed and provided feedback on the manuscript (5%). Letitia Deng assisted with data collection (2%). Eoin O'Gorman reviewed and provided feedback on the manuscript (2%). Barbara Bollard Breen reviewed and provided feedback on the manuscript (1%).

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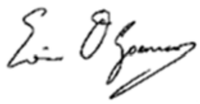 

Dr. Eoin O'Gorman Letitia Deng

Publications associated with this thesis

Peer-reviewed journal publications

Nishar, A., S. Richards, D. Breen, J. Robertson, and B. Breen. (2016a). Thermal infrared imaging of geothermal environments and by an unmanned aerial vehicle (UAV): A case study of the Wairakei – Tauhara geothermal field, Taupo, New Zealand. Renewable Energy 86: 1256-1264.

Nishar, A., S. Richards, D. Breen, J. Robertson, and B. Breen. (2016b). Thermal infrared imaging of geothermal environments by UAV (Unmanned aerial vehicles). Journal of Unmanned Vehicle Systems.

Nishar A, Breen D, Lawrence G, Breen B (2016c) Responses of Vegetation to Temperature Gradients around Geothermal Features: A Review on Wairakei – Tauhara Geothermal Field, Taupo, New Zealand. Geoinfor Geostat: An Overview 4:3.

Manuscripts in review

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Thanks to all my friends for understanding why I could not spend time with them over most weeks. A huge thank you to my Amma and Abba for encouraging me and being there all the way. Many thanks to Mahirul Maasi for her moral support and for always checking on my progress. Finally, I extend my deepest thanks to my wife for her continuous support and encouragement. Zaira, you are an amazing person, and this was only achieved because I had you by my side.

Chapter 1

Introduction

1.1 Background

Global temperatures are predicted to increase significantly in the near future, becoming a worldwide public concern (Sato, Kimura, & Kitoh, 2007). Current reports indicate an average global temperature increase of 0.85°C since 1880 and a minimum increase of 2°C during the next century (IPCC, 2014). Evidence for the ecological impacts of global warming at species and population levels is already substantial (Parmesan & Yohe, 2003; Walther, 2010). Despite being highly topical, warming and its consequences on vegetation are poorly understood (Richardson & Poloczanska, 2008; Rosenzweig et al., 2008; Woycheese, 2009). A growing amount of evidence shows that warming is having profound effects on vegetation (Draper, 2010; Parmesan, 2006) and studies suggest that warming will affect all members of the plant community that serve as regulators to many important cycles in Earth's ecosystems (Easterling et al., 2000; Zhao, Wu, Yin, & Yin, 2011). Consequently, government and non-government organisations are investing further resources (Cossia, 2011) to understand and estimate the full extent of the impact on vegetation communities caused by global temperature increases.

At present, various models are used to investigate the impact of warming (Canadell et al., 2007; Franchito & Rao, 1992). Warming experiments use a variety of heating methods, including electric heating (de Valpine & Harte, 2001), infrared radiation (Wan, Luo, & Wallace, 2002), reciprocal transplants (Jonasson, Havström, Jensen, & Callaghan, 1993), and open and closed-top field greenhouses (Henry & Molau, 1997). While these approaches have contributed to our understanding of global warming, each of these methods comes with its set of limitations. Some experiments have warmed only parts of the ecosystem (e.g. below or above ground), while others have warmed the ecosystem for only part of each day or year (Shaver et al., 2000). However, using these models to predict the effects of warming largely ignores climate-ecosystem interactions (Leuzinger, Fatichi, Cusens, Niklaus, & Körner, 2015). Laboratory studies provide key insights into mechanistic processes (Beveridge, Humphries, & Petchey, 2010), but they lack the interactions of a natural ecosystem (Yvon-Durocher, Jones, Trimmer, Woodward, & Montoya, 2010), which may become a barrier to fully understanding ecosystem-level responses to warming by vegetation. In addition, long-term manipulations of temperature are critical, but such studies are uncommon because of the physical and financial challenges of experimental warming at this scale (Canhoto, de Lima, & de Almeida, 2013; Melillo et al., 2011).

In this thesis, I trial a warming experiment approach using natural thermal gradients occurring around geothermal features. Geothermal features prevail over long time periods (Bibby, Caldwell, Davey, & Webb, 1995) and their effects on vegetation, caused by elevated levels of surface temperature, are thus long-term. Therefore, geothermally heated ecosystems present an excellent opportunity to investigate the response of vegetation to warming within a global warming context. Geothermal gradients have been used to illustrate the biological effects of temperature in a range of terrestrial and aquatic environments (Sayeh et al., 2010) with the focus of understanding life in extreme environments. Geothermal ecosystems offer a low-cost solution to investigate temperature, acting as a sentinel system by highlighting early responses to warming.

1.2 Research question and objectives

Research Question: Using a natural geothermal environment, how can we understand the effects of warming on vegetation?

To answer this research question, I have three research objectives:

Objective 1: Review the responses of vegetation to temperature gradients around geothermal features.

Objective 2: Establish the current thermal characteristics of the Wairakei-Tauhara geothermal field

Objective 3: Evaluate the effects of soil temperature on biomass and vegetation regeneration in a geothermal system.

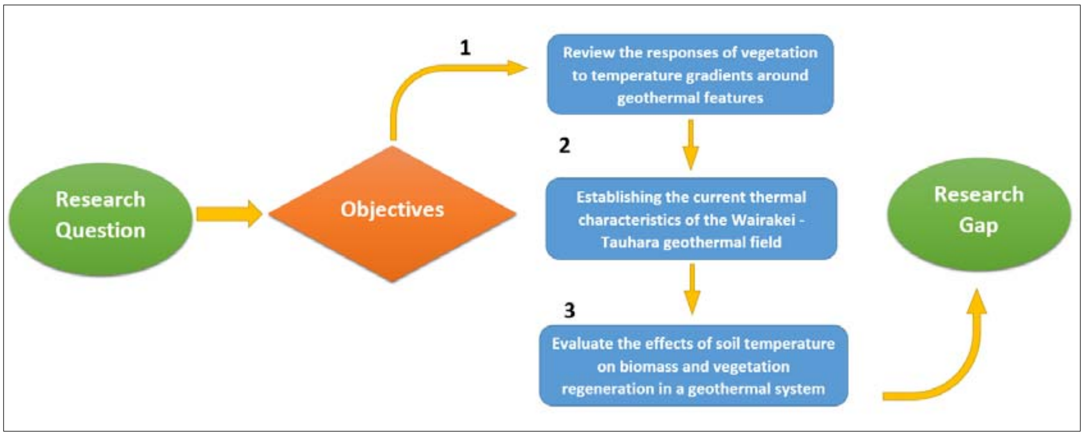


Figure 1. Research programme.

I achieve each of these three objectives in Chapters 3 to 5, respectively. Firstly, in Chapter 3 I demonstrate, using historical aerial and thermal infrared imagery, how the vegetation in the study area responds to temperature gradients around geothermal features (Objective 1). Secondly, in Chapter 4 I demonstrate the methodology for thermal infrared data collection using an unmanned aerial vehicle and data processing (Objective 2). Thirdly, in Chapter 5, using regrowth methods, I investigate the impact on the vegetation of geothermally heated soil systems (Objective 3). Finally, in the discussion (Chapter 6), I show how geothermal ecosystems provide an ideal platform for conducting warming research that will help disentangle the response of vegetation to warming.

1.3 Originality of thesis

This thesis addresses a critical gap in vegetation dynamics research by using a natural setting as a warming experiment. As such, this thesis serves as a pilot study for researchers about how to undertake warming experiments in a geothermal environment that includes climate-ecosystem interactions. By identifying the feasibility of a geothermal environment as a natural laboratory, this approach can assist to highlight early responses to warming, and improve understanding of how to manage and implement strategies that will help safeguard against the impacts of temperature changes.

In Chapter 3, I review vegetation responses to temperature gradients around geothermal surface features over time, using historical thermal infrared images and aerial photographs. This review unveils the influence that soil temperature gradients have had on vegetation over the years and gives us an indication of the level of impact on vegetation that can be expected with soil warming. In Chapter 4, I demonstrate how to capture both aerial and thermal infrared imagery using a UAV and a methodology to process the data and make it available for analysis. In Chapter 5, using vegetation regeneration plots around geothermal features, I demonstrate the influence that elevated soil temperature has on root biomass and vegetation regeneration.

While the effects of warming have been investigated, no studies exist that used an entirely natural environment with undisturbed ecosystem interactions and a natural heat source. The use of UAVs to capture thermal infrared imagery in this study is not only a novel application; it also sets a protocol for industry and research applications. The time series study using historical aerial photos demonstrates how to extract data from black and white scanned imagery and imagery with compromised quality.

All of my three findings chapters have been submitted to international peer-reviewed journals. Three papers have been accepted, and one is in review.

1.4 Rationale for research design

The thesis case study was undertaken at the Wairakei-Tauhara geothermal field, Taupo, New Zealand (Figure 2). The Wairakei-Tauhara geothermal field is currently being developed for geothermal power with large areas of the field protected and allocated to nature reserves. The section of the Wairakei-Tauhara geothermal field covered by this study is referred to as the Crown Road geothermal area, covering an area of about one km^2. The study site is a Maori reserve owned by the Tauhara Middle 15 Trust who consented to this study being conducted on their land. Of all the geothermal fields in the Taupo Volcanic Zone, the Wairakei-Tauhara geothermal field is the most studied and there is a variety of biophysical and thermal data available.

While my methods provided context-specific insights, the methods themselves have not been used widely. Consequently, the methods developed in this thesis could be broadly generalised to different geothermal systems to provide context-relevant insights. As a result, I have been able to develop methods that made a direct contribution to vegetation dynamics research in New Zealand, while also addressing a critical gap in experimental soil warming methods.

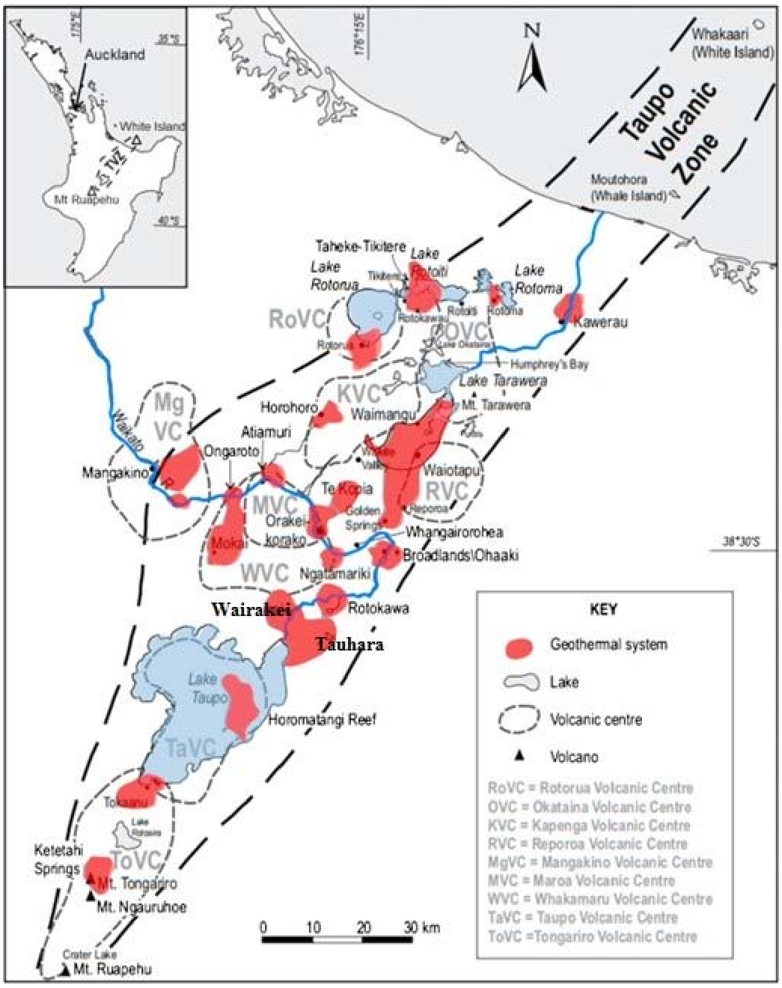


Figure 2. Locations of geothermal fields, surface hydrology and volcanic centres in the Taupo Volcanic Zone (Ratouis & Zarrouk, 2016).

1.5 Thesis organisation

This thesis is organised into six chapters (Table 1). In Chapter 1, I introduce the thesis and outline the thesis aim and objectives. In Chapter 2, I establish the context of my research through a literature review. Chapters 3 to 5 are my study chapters developed from peer-reviewed manuscripts. In Chapter 6, I bring together the main findings of this thesis and discuss how these findings achieve the thesis aim.

Table 1. Thesis organisation by chapter, outlining purpose and methods used.

Chapter	Purpose	Methods
1 Introduction	• Describe research problem • Outline thesis aims and research objectives • Identify the originality of the thesis • Describe the organisation of the thesis	• Literature review
2 Literature review	• Establish context of the research • Introduce relevant literature • Highlight current knowledge gaps	• Literature review
3 Study 1	• Study 1 to achieve Objective 1 • Resample historical imagery for data extraction and processing • Detect changes in vegetation pattern over time • Identify the influences of geothermal systems in vegetation	• Literature review • GIS and remote sensing application • Classified in ENVI
4 Study 2	• Study 2 to achieve Objective 2 • Capture aerial and TIR data using UAV • Demonstrate methodology for data capture • Demonstrate methodology for data processing	• Literature review • Operate UAV and sensors • PIX 4D and GIS application
5 Study 3	• Study 3 to achieve Objective 3 • Setup vegetation regeneration plots • Examine the impact soil warming has on vegetation • Test the variable with the greatest influence on vegetation.	• Literature review • Fieldwork for data collection • Data analysis
6 Discussion	• Summarise the main findings of the thesis and how they relate to the thesis aim • Describe the implications of this research • Demonstrate original contributions to the field • Describe remaining knowledge gaps • Identify future research questions	• Literature review • Critique of work • Self-reflection

Chapter 2

Literature review

2.1 Overview

This literature review will introduce relevant research and establish the context of my research. First, I outline the characteristics of geothermal areas and their relevance for plant cover. Second, I discuss how geothermal features can assist in understanding the impact of warming on vegetation. Third, I discuss the current monitoring practices that are in place to detect the vegetation changes. Finally, I outline the case study at the Wairakei-Tauhara geothermal field in Taupo, New Zealand used to demonstrate the methodology and develop the research aims in this thesis.

2.2 Characteristics of geothermal areas and their relevance for plant cover

2.2.1 Heat characteristics of geothermal areas

Geothermally active areas are unique environments regarding geology and biology. Despite extreme conditions, geothermal areas host unusual vegetation and rare plant species of high conservation value. Due to high crustal heat flow (Kratt, 2005) surface and soil heating (Cody, 2007) is a common characteristic of geothermal areas. Soil heating occurs when there is an increase in temperature in the soil layer (Verburg, Van Loon, & Lükewille, 1999), while Earth's surface heating is the increase of sensible heat (Jones et al., 2007). Soil temperature is normally measured at a depth of 10 to 15 cm because at this depth, the soil remains undisturbed and the soil temperature is buffered (Norris, Wraith, Castenholz, & McDermott, 2002). Knowing the range of soil temperature gives a good indication of the geothermal heat gradient in the particular geothermal field (Greve, 2005). The geothermal temperature gradient is the primary geothermal parameter used to describe characteristics of the geothermal field (Yuan et al., 2009), and used as an indicator while geothermal resource exploration e.g.(Tissot, Pelet, & Ungerer, 1987).

The geothermal gradient is depth dependent (Gong, Wang, Liu, Guo, & Cai, 2003) and significantly influenced by heat production and flow (McGee, 1997) and rock conductivity (Yuan et al., 2009). Karapiti is a very active geothermal area in New Zealand and this is known from random soil temperature at various depths (Figure 3, Table 2). However, for geothermal resource extraction, the heat gradient is at a much higher depth and different geological layers are required (Mohamed et al., 2015).

Figure 3. Karapiti geothermal field, Taupo, New Zealand.

Table 2. Soil temperature versus depth at random site, Karapiti Geothermal area, Taupo, New Zealand (from Given, 1980).

Site	Soil temperature (°C)	Depth (cm)
1	97	1.5
2	97	3
3	97	7
4	97	13
5	97	24
6	85	15
7	80	15
8	60	15
9	40	15

Soil surface temperature is affected by weather and seasonality (Florides et al., 2011), but in geothermal areas, surface heat loss also contributes to the variation in surface temperature (Čermák, Šafanda, Krešl, Dědeček, & Bodri, 2000). The high temperature from within the Earth's crust forces a continuous flow of heat to the earth's surface, bringing thermal energy closer to the surface (Bowen & Bowen, 1989; Koenig & McNitt, 1983; Wisian, Blackwell, & Richards, 1999). The surface heats up as the hot fluids and steam from the deepest parts of a geothermal system moves independently towards it (Cody, 2007). Despite the continuous transfer of heat to the surface, due to wind, the heat at the surface dissipates very quickly (Gan, 2015).

A change in soil temperatures is a serious threat to the vegetation community (Siddiqui et al., 2016). When under high-temperature stress, plant growth metabolism is altered by disturbing protein stability, enzymatic activity and carbohydrate metabolism (Lavania, Dhingra, Siddiqui, Al-Whaibi, & Grover, 2015; Sangu, Tibazarwa, Nyomora, & Symonds, 2015). Soil warming can affect the fertility of soil (Clair & Lynch, 2010), the capability of the root system for acquiring water (Kramer & Boyer, 1995) and nutrients (Engels, Kirkby, & White, 2012); limiting plant growth and development. Researchers have claimed that under heat stress, roots modify their physiology, longevity, morphology and architecture to allow adequate nutrient uptake (Chapin, 1980; Clarkson, 1985; Lynch, 1995). Furthermore, plant cell size reduces at a higher soil temperature, there is curtailed water loss, increased stomatal and densities, and greater xylem diameter of both root and shoot (Bañon et al., 2004). Heat stress also affects the formation of microtubule in cells and causes the elongation of cells (Smertenko, Draber, Viklický, & Opatrný, 1997). At the sub-cellular level, major modifications occur in chloroplasts, leading to significant changes in photosynthesis (Karim, Fracheboud, & Stamp, 1997). It is evident that high temperature considerably affects anatomical structures not only at the tissue and cellular levels but also at the sub-cellular level (Wahid, Gelani, Ashraf, & Foolad, 2007) and lead to carbon starvation and inhibition of growth (Schöffl, Prandl, & Reindl, 1999).

Increased soil temperature has been demonstrated to correlate with a large number of soil parameters (Boothroyd, 2009), which in turn are strongly correlated with variation in vegetation composition and structure (Burns, 1997). Furthermore, many studies reported that non-vascular plants dominated geothermal areas due to higher temperature tolerance of non-vascular plants (Convey & Smith, 2006; Convey, Smith, Hodgson, & Peat, 2000; Glime & Hong, 1997; Glime & Iwatsuki, 1997). The heat tolerance of normal plant cell activity has been shown to range from 45-55ºC (Elmarsdottir, 2003) although some cells can survive at higher temperature (Konis, 1949). Non-vascular plants such as mosses can survive in high temperature geothermal areas well. This can be explained by the lack of roots and that soil temperature is lower at the soil surface than for instance at 10 or 15 cm depth (Given, 1980; Glime & Hong, 1997). Similarly, vascular plants found in geothermal areas have more but short roots (Stout, Summers, Kerstetter, & McDermott, 1997), a consequence of heat stress (Abeles, Morgan, & Saltveit, 1992). It was concluded that vascular plants were limited primarily by root zone temperature, with higher temperatures favouring mosses and lichens.

A study by Burns (1997) examined the vegetative composition and structure along a temperature gradient at Te Kopia geothermal field in Taupo, New Zealand where he found soil temperature was the primary determinant of plant species composition. Given (1980) concluded that at Karapiti geothermal area also in Taupo, New Zealand, the heat flow through the soil was probably the most significant factor in determining species composition, with non-vascular plants occupying the hotter zones. Sheppard (1971) performed a spatial analysis of vegetation patterns at the Yellowstone National Park geothermal sites, Wyoming, USA, and noted that numerous species of mosses survived in areas where soil temperatures reached 50-65 °C at a depth of 10 cm.

Carbon allocation and carbohydrate content in roots are significantly reduced in high soil temperature. Moreover, it is this interruption of carbohydrate supply in the root system that has been suggested as a primary factor responsible for growth inhibition and root dysfunction of plants grown at high soil temperatures (Du & Tachibana, 1994). This explains the reason for shallow root systems and short stature of vascular plants found in geothermal areas. Furthermore, reduced amounts of carbon in root systems of high temperature soil impede protein synthesis and cell-wall maintenance (Huang, Rachmilevitch, & Xu, 2012).

2.2.2 Soil and air chemistry characteristics in geothermal areas

Soils that occur in active geothermal areas with elevated temperature show altered chemistry (Appoloni, Lekberg, Tercek, Zabinski, & Redecker, 2008). Elevated levels of Calcium (Ca), Iron (Fe), Potassium (K), Magnesium (Mg), Manganese (Mn), Phosphorus (P), Boron (B), Sulfate (SO_4^2), Cadmium (Cd), Copper (Cu), Nickel (Ni), Lead (Pb), Zinc (Zn) have been detected in geothermal areas (Fournier, 1977; Henley, Hedenquist, & Roberts, 1986; Rodman, Shovic, & Thoma, 1996). On the contrary, farmland quality soil contains expected levels of Nitrogen (N), Potassium (K), Phosphorus (P), organic carbon (C) and other organic matter (Larson & Pierce, 1994; Romig, Garlynd, & Harris, 1996)

Due to the unique soil chemical characteristics in geothermal fields, only a limited range of plants can grow in geothermal areas and are restricted to a few species (Appoloni et al., 2008). These include: *Kunzea ericoides* var. *microflora* (van Manen & Reeves, 2012), *Campylopus capillaceus* (Burns, 1997) and *Leptospermum scoparium* (Burns, Ward, & Downs, 2013). Elevated levels of chemicals highly influence plant distribution (Burns, 1997), growth rate and plant height (Brownsey & Chinnock, 1984). Such chemical constraints allow for the least sensitive plants to thrive and hence become endemic to the area (Boothroyd, 2009). For example, in New Zealand, the *Kunzea* shrub grows exclusively in the geothermal areas of Waikato region (de Lange, 2014) and with a small amount of habitat available, they are considered to be threatened (De Lange et al., 2009). According to Given (1980) geothermal plants are endemic to these areas due to their genetic and physiological adaptations to the environment and are often found to be subspecies of taxa that are common in non-geothermal areas (Given, 1995). These include: *K. ericoides* var. *microflora* (Prostate Kanuka) is a subspecies of *K. ericoides* (white tea kanuka).

Furthermore, geothermal vents emit a range of non-condensable gases into the air (Rodríguez, 2014). As these gases settle in the surrounding ecosystems (Paoli & Loppi, 2008), they impact on plants and other ecosystem components (Bayer, Rybach, Blum, & Brauchler, 2013). Generally, geothermal emissions from vents are made up of 73-98% carbon dioxide (CO_2), 1-24% hydrogen sulfide (H_2S), 0.02-0.65% methane (CH_4), 0.1-8% hydrogen (H_2), 0.3-16% nitrogen (N_2), 0.1-3% argon (Ar), and traces (<0.001%) of radon (Rn), boron (B), mercury (Hg), arsenic (As), antimony (Sb), and ammonia (NH_3) (Baldi, 1988; Bargagli, Cateni, Nelli, Olmastroni, & Zagarese, 1997; Bussotti et al., 2003; Gunerhan, 1999; Loppi, 2001; Rodríguez, 2014). Of these gases, Thompson and Kats (1978) studied the effects of H_2S on crop and forest plants and reported that with 30-100 ppb level of H_2S gas, plant showed continuous fumigation while 300-3000 ppb caused patches of dead cells on leaves, defoliation and stunted growth. Furthermore, H_2S is unstable in air and will oxidise to SO_2 (Kellogg, Cadle, Allen, Lazrus, & Martell, 1972). High levels of SO_2 could lead to leaf necrosis and defoliation (Prinz & Brandt, 1985), interfering with the cellular membranes and enzyme activity affecting biochemical process in the cell (Wellburn, Majernik, & Wellburn, 1972).

2.3 The use of geothermal fields for climate change studies

Geothermal systems occur in regions of high crustal heat flow that are related to the presence of hot rocks located deeper in the crust (DiPippo, 2005). According to Cody (2007), surface or ground heating is caused by very hot fluids and steam (up to 300ºC) from the deepest parts of a geothermal system, moving towards the surface. When hot water rises to the surface, it encourages the formation of geothermal features such as hot springs, fumaroles, geysers and mud pots (Heasler, Jaworowski, & Foley, 2009).

As discussed in Sections 2.2.1 and 2.2.2, heated ground in a geothermal system creates a hostile environment for vegetation. In geothermal fields, vegetation establishment and growth is limited by several chemical and physical factors, strongly controlled by the thermal gradient (section 2.2.1 and 2.2.2, pp. 10-15). Studies of geothermal systems are traditionally focused on determining and interpreting the composition of geothermal fluids and gas emerging from the geothermal reservoir (Arnórsson, Stefánsson, & Bjarnason, 2007) rather than their ecological interactions. However, O'Gorman et al. (2014) suggested that geothermal gradients of geothermally heated ecosystems presented an excellent opportunity to investigate the responses of vegetation to temperature change. This suggestion was based on the Dunne et al. (2004) approach of embedding manipulative warming experiments within multiple sites along a natural thermal gradient, better enabling the investigation of responses to temperature change. Natural soil warming studies such as along the geothermal gradient will allow testing of single against multiple factors and tease out the plant's response to warming (Williams & Jackson, 2007).

Many studies e.g. (Burns, 1997, Convey, Smith, Hodgson, & Peat, 2000, Sayeh et al., 2010) have demonstrated the use of geothermal gradients for understanding the biological effects of temperature in a range of environments. Similarly, vertical heat distribution and soil warming caused by geothermal systems can assist with monitoring vegetation responses to warming (Schulze, 1999).

Heat in geothermal areas warms the soil continuously while the heat that is transferred to the air dissipates very quickly (Heasler, Jaworowski, & Foley, 2009). The thermal distribution on the surface reflects changes in the conditions of the growing environment proportional to the distance from a heat source point (Kershaw, 1985). Since geothermal heat is transported from the deep crust, it mainly heats the soil and the roots of vegetation found in the area (Elmarsdottir, Ingimarsdottir, Hansen, Olafsson, & Olafsson, 2003). As a result, uneven spatial distribution patterns have been observed in vegetation communities surrounding geothermal features (Burns, 1997; Given, 1980; Stout, Summers, Kerstetter, & McDermott, 1997).

The global average temperature increased by 0.74 °C in the 100 years from 1906 to 2005 and an additional increase of 1.8-4.0 °C is expected by the end of this century (IPCC, 2015). Hence, any simulation experiments in the field need to accommodate the predicted temperature range. Such studies can contribute to modelling biotic responses of vegetation to warming and particularly assist in estimating community shifts with changing temperatures (Dunne, Saleska, Fischer, & Harte, 2004; Menzel et al., 2006). High-temperature geothermal fields are especially common around tectonic plate boundaries, although less extreme areas can be found throughout the globe (Shapiro & Ritzwoller, 2004). In addition, geothermal systems are not confounded by soil chemistry (Duggan, Boothroyd, & Speirs, 2007; Norris, Wraith, Castenholz, & McDermott, 2002) and are ideal for isolating the effects of temperature on vegetation.

Despite the species richness, many studies (Convey & Smith, 2006; Given, 1980; Glime & Hong, 1997) have shown that the vegetation of geothermal areas is dominated by bryophytes. However, vascular plants dominate the vegetation of the Wairakei-Tauhara geothermal field. Prostrate kanuka (*Kunzea tenuicaulis)* is common at the margins of the geothermal areas with scattered broom (*Cytisus scoparius)*, blackberry (*Rubus fruticosus*), buddleia *(Buddleja davidii),* gorse (*Ulex europaeus)* and exotic grasses (Wildlands.2011). Prostrate kanuka is well adapted to geothermal areas, due to which a slight temperature shift alters its distribution (van Manen & Reeves, 2012) Prostrate kanuka is not only endemic to New Zealand but also a threatened and at risk plant (de Lange, 2014).

2.4 Monitoring plant cover

The distribution patterns of vegetation can be used as indicators of underlying environmental conditions (Brossard, Elvebakk, Joly, & Nilsen, 2002; Karlsen, Elvebakk, & Johansen, 2005). Vegetation monitoring efforts have significantly increased in recent years, mainly triggered by climate change (Masson-Delmotte et al., 2012; Post et al., 2009). Vegetation cover is an integrating component between soil, water and atmosphere and plays a key role in studying effects of global warming on the ecosystem and its feedback to the warming process (Hinzman et al., 2005; McGuire et al., 2002).

Given its recognised importance, many organisations and governments actively seek to understand the spatial and temporal dynamics of vegetation through monitoring processes (Bennett, Peterson, & Gordon, 2009). Monitoring can help determine the extent and cause of changes to vegetation such as: changes in abundance of species and diversity (Dale et al., 2001); incursion of threats from invasive species (Molnar, Gamboa, Revenga, & Spalding, 2008; van Manen & Reeves, 2012); change in vegetation cover (Ringrose, Vanderpost, & Matheson, 1996); and stress due to competition and changes in growth conditions (Lawley, Lewis, Clarke, & Ostendorf, 2016).

2.4.1 Ground-based monitoring.

The main objective of many ecological monitoring programs is to detect changes in ecosystem functions and processes (Niemi & McDonald, 2004). Vegetation cover and composition are two of the most commonly used indicators used to evaluate land degradation, recovery and the success of restoration (Godínez-Alvarez, Herrick, Mattocks, Toledo, & Van Zee, 2009). A large number of methods are currently used to quantify various forms of these indicators (Elzinga, Salzer, Willoughby, & Gibbs, 2001). In-growth core methods have been used to estimate fine root turnover (Hendrick & Pregitzer, 1993). The in-growth core method is preferred for high-quality data when it comes to root observations and defining belowground net primary production (S. Chen et al., 2016). Embedding a mesh container filled with root-free soil provides accumulative root biomass growing into the mesh container (Hendricks et al., 2006). The in-growth period varies widely among ecosystems, from two weeks in crops (Steingrobe, Schmid, & Claassen, 2001) to up to three years in a Norwegian forest (Ostonen, Lõhmus, & Pajuste, 2005). For grassland and shrubs, the ingrowth period has ranged from three to seven months (Garcia-Pausas, Casals, Romanyà, Vallecillo, & Sebastià, 2011; J. Li, Lin, Taube, Pan, & Dittert, 2011).

Furthermore, clear-cutting with natural regeneration is another technique used for vegetation growth monitoring (Keenan & Kimmins, 1993). Clear-cutting can assist understanding vegetation establishment, growth, early succession and general impact on above-ground vegetation (Kembel, 2009). The regeneration after clear-cutting is determined by precipitation, radiation, and soil nutrients (Splawinski, Gauthier, Bergeron, Greene, & Valeria, 2016). Regeneration is measured as biomass increment over time (Xiang et al., 2014). Clear-cutting causes severe disturbances and the recovery rates differ for each species (Amiro et al., 2010). Clear-cutting has been found valuable for comparing regeneration and understanding the underlying cause of the vegetation responses (Khomik, Williams, Vanderhoof, MacLean, & Dillen, 2014).

2.4.2 Airborne monitoring

Methods for monitoring vegetation conditions have traditionally involved site-based assessments (Gibbons & Freudenberger, 2006). However, the increasing demand for information at broader scales has seen the application of spatial modelling (Zier & Baker, 2006) as well as remote sensing and Geographical Information System (GIS) for mapping and monitoring indicators of vegetation conditions. Data used for this purpose are, typically, aerial imagery (Ciminale, Gallo, Lasaponara, & Masini, 2009; Hamandawana, Eckardt, & Chanda, 2005). Table 3 lists the common types of aerial imagery used for vegetation monitoring. The advantage of using aerial imagery is that it provides a time-specific state of the vegetation and covers a range of spatial scales and spatial and spectral resolutions.

Table 3. Type of aerial imagery and their use for vegetation monitoring.

Type of Aerial Imagery	**Use in Vegetation Monitoring**
Colour aerial photo	Long-term vegetation change, e.g. (Masubelele, Hoffman, & Bond, 2015)
Near-Infrared imagery	Monitoring vegetation condition and phenology, e.g. (Knoth, Klein, Prinz, & Kleinebecker, 2013)
Thermal Infrared imagery	Monitor hydrothermal and geothermal vegetation growing conditions, e.g. (Neale, Jaworowski, Heasler, Sivarajan, & Masih, 2016; Nishar, Richards, Breen, Robertson, & Breen, 2016b)
LiDAR	3-D information regarding vegetation structure, e.g. (Bater et al., 2011)

Change detection studies of long-term time series data require both recent and historical data (Nagarajan & Schenk, 2016). Visual and infrared imagery potentially offer radiometric and geometric details about the appearance and changes of past landscapes (Risbøl, Briese, Doneus, & Nesbakken, 2015). With the emergence of new computer techniques (Hirschmuller, 2008), it is now possible to extract more information out of historical imagery (Sevara, 2013; Verhoeven, Doneus, Briese, & Vermeulen, 2012).

Monitoring projects based primarily on aerial imagery, greatly benefit from repeated aerial data capture within pre-defined intervals in combination with fieldwork (Dramstad et al., 2001). The costs for aerial imagery acquisition using manned aircraft is high, not only due to the equipment but also due to labour required for airtime, ground support and image processing. Delays due to weather conditions can increase the cost (Beck, Booth, & Kennedy, 2014). Most of these limitations can be overcome by the use of Unmanned Aerial Vehicle (UAVs). UAVs are remotely controlled, unmanned, reusable motorised aerial vehicles that can carry various types of payloads or cameras designed for specific purposes (Bhardwaj, Sam, Akanksha, Martín-Torres, & Kumar, 2016). UAVs are increasingly used for research, monitoring and surveillance (Bemis et al., 2014; Clapuyt, Vanacker, & Van Oost, 2016; Gomez, Hayakawa, & Obanawa, 2015; Nishar, Richards, Breen, Robertson, & Breen, 2016a).

UAV platforms provide the flexibility to choose appropriate data acquisition periods and data types (Vollgger & Cruden, 2016). They also allow easy adjustments in flying altitude to obtain very high spatial resolution while maintaining viewing angles and sufficient forward and side image overlap. The cost of these data acquisition methods is substantially lower than obtaining imagery captured by commissioning manned flights. Although the use of UAVs for research is still in its infancy (Nishar et al., 2016b), the prospects of this technology are immense. This new approach of using UAV platforms, as well as the advances in photogrammetry, is proving to be very effective (Hugenholtz et al., 2013). By using UAVs, it is now possible to capture imagery at sub-centimetre resolution and with high positional accuracy. The advent of lightweight, low-cost UAVs coupled with various remote sensors is revolutionising research prospects. In addition to hardware developments, software packages are effectively contributing to the production of accurate and high-resolution digital surface models (DSMs), digital terrain models (DTMs) and ortho-mosaics (Fonstad, Dietrich, Courville, Jensen, & Carbonneau, 2013; Turner, Lucieer, & Watson, 2012). Using a UAV as an aerial platform also brings significant health and safety advantages. UAV remote sensing features high spatial resolution, low temporal resolution and the ability to operate with cloud cover and at low altitude (Saberioon et al., 2014). Herwitz et al. (2004), Kooistra et al. (2014) and Hunt et al. (2010) had great success in vegetation data extraction made possible by low altitude flying and high spatial resolution multispectral imagery captured by UAV.

2.5 Case study: Wairakei - Tauhara geothermal field, Taupo, New Zealand

The Taupo Volcanic Zone (TVZ) is an area of intense geothermal activity in the North Island of New Zealand (Kissling & Weir, 2005; Soengkono, 1995), covering approximately 30 by 150 kilometres and containing 23 geothermal fields or systems (Bibby et al., 1995). The TVZ contains all but one of New Zealand's geothermal systems (Heise et al., 2007). It is situated above a subduction zone, where the Pacific plate is subducted beneath the Australasian plate (Wilson et al., 1995). The high temperature geothermal areas in the TVZ (Figure 2, Chapter 1, p. 7) predominantly span three Districts (Taupo, Rotorua and Kawerau) and two regions (Bay of Plenty and Waikato).

Steam temperatures of over 300°C are recorded for the geothermal systems within the TVZ (Kissling & Weir, 2005). The geological structure of TVZ geothermal fields was examined by Wood (1995) who concluded that the majority of the fields were located at the margins of major volcanic craters. Bibby et al. (1995) stated that the geothermal systems, once formed, are stable and long-lived features. Geothermal fields are typically

5 to 25 km^2 in areal extent (Bibby et al., 1995) and appear to be regularly spaced across the TVZ, with an average separation of about 15 km (McNabb, 1992; Wooding, 1976).

Due to its suitability for power generation, the TVZ has received previous attention by investors (Brown & Simmons, 2003; Krupp & Seward, 1987; Wilson, Webster-Brown, & Brown, 2007). The Wairakei-Tauhara geothermal field was the first to be explored and developed in New Zealand, with initial research, design and construction of the power station taking place between 1948-1963 (Rosenberg, Bignall, & Rae, 2009). Management of the Wairakei-Tauhara geothermal field has evolved during more than 50 years of resource development while being the centre of geothermal-related geological and geophysical research (Thain & Carey, 2009). Resource utilisation and development within the Wairakei-Tauhara geothermal field is regulated by consents granted through the Waikato Regional Council (http://www.waikatoregion.govt.nz). These consents control and review the operations within the geothermal field as well instruct regular environmental monitoring to investigate any adverse effects to the geothermal development. The Waikato Regional Council is also responsible for encouraging continuous research within the geothermal environment to increase the understanding of these geothermal features. The Wairakei-Tauhara geothermal system is comprised of two sectors; Wairakei in the north-west and Tauhara in the south-east (Figure 4). Drawing on geological data, Grindley, Harris, and Steiner (1965) estimate the age of the Wairakei-Tauhara geothermal field to be > 0.5 Ma. The Wairakei-Tauhara geothermal field appears to have maintained activity during recent volcanism (Simmons, Keywood, Scott, & Keam, 1993), and hosts the largest observed heat flows in the TVZ (Kissling & Weir, 2005).

The Wairakei-Tauhara geothermal field hosts a dynamic ecosystem. A study of the vegetation that thrives in the high-temperature (50-60ºC), ecosystem of the Wairakei-

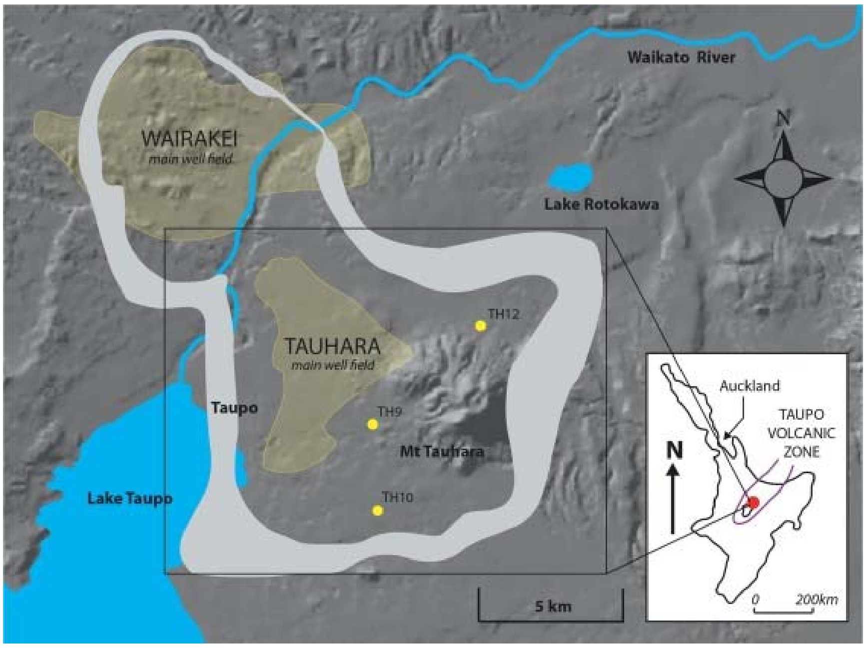


Figure 4. Map of the Wairakei-Tauhara geothermal field (Mauriohooho, Barker, & Rae, 2016).

Tauhara geothermal field will lead to a better understanding of how vegetation manages to survive despite temperature constraints. It will also promote our understanding of the vegetation's response to temperature extremes, entirely in line with other approaches that have been used in several high temperature systems to improve ecological understanding (Barnes, Crosby, Jones, Wright, & Hogan, 1994; Pace, 1991; Reysenbach, Ehringer, & Hershberger, 2000).

Currently, geothermal areas are extensively studied to investigate their aptitude for electricity generation. However, a lack of studies and literature on the ecological monitoring of geothermal areas, specifically a lack of interest in monitoring vegetation has motivated this study. The combination of ground-based measurements and aerial imagery will demonstrate a unique approach to understanding the characteristics of the geothermal environment and the responses of the vegetation to those characteristics.

Chapter 3

Responses of vegetation to temperature gradients around geothermal features.

Objective 1: Review the responses of vegetation to temperature gradients around geothermal features.

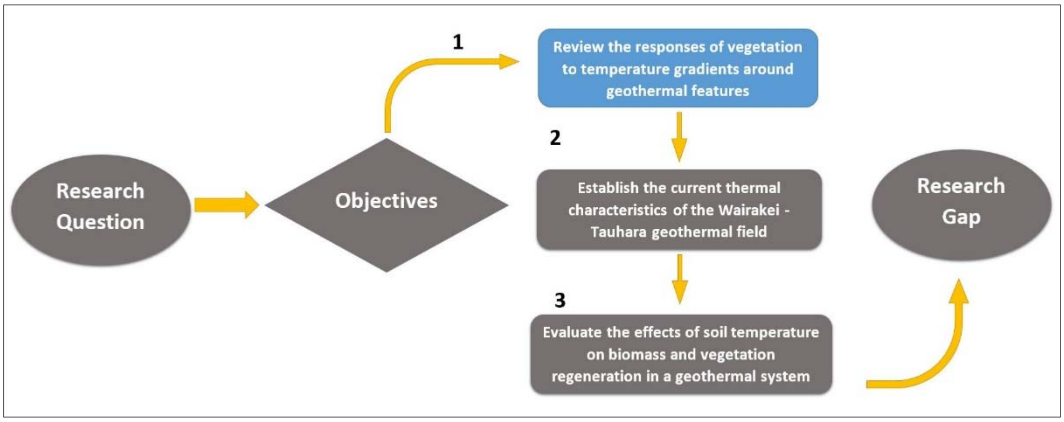


Figure 5. Objective 1.

A version of this chapter has been published as;

Nishar A, Breen D, Breen B (2016). Responses of Vegetation to Temperature Gradients around Geothermal Features: A Review on Wairakei-Tauhara Geothermal Field, Taupo, New Zealand. Geoinfor Geostat: An Overview 4:3.

Geothermal ecosystems experience extreme conditions but can support unique communities of organisms. This study uses historical thermal infrared images and aerial photographs to review the vegetation responses to temperature gradients around the geothermal surface features of the Wairakei-Tauhara geothermal field. Here, the spatial distribution of ‘‘geothermal kanuka’’, *Kunzea tenuicaulis* and related species and hybrids were mapped in relation to ground temperatures measured from the thermal infrared images. Optimal growing conditions for these plant communities in the geothermal area were at ground higher than ambient temperatures higher. Areas of moderate to high surface heat continued to support plant communities, but as the ground surface temperature was reduced, vegetation growth and establishment increased. The results presented here demonstrate the impact of surface temperature on vegetation and suggest that long-term temperature intensification or reduction over an area does not wipe out vegetation completely. In this case, geothermal kanuka was able to adapt to changes in the temperature and increase its distribution. Understanding how these plants survive in high-temperature ecosystems may provide insight into how they cope with changes in temperature in these and other extreme habitats and how other species may respond to future climate change. An awareness of the interactions between temperature and plant community structure can help plan conservation strategies.

3.1 Introduction

Geothermal features in New Zealand host distinctive assemblages of plants that survive under extreme geophysical and geochemical conditions (Boothroyd, Stark, Collier & Winterbourn 2000; Death & Death, 2006; Given, 1980; Healy, 1992). Steep temperature gradients, elevated levels of gases and minerals and low pH create harsh but specialised niches for unique bacteria, algae, plants and animals (Burns, 1997, Boothroyd, 2009). Despite their ecological significance (Given, 1980; Huser, 1991), only a few studies have examined the relationship between these environments and their unique biota (Boothroyd, 2009). Winterbourn and Brown (1967) observed that the distribution of fauna around streams in the Taupo region was related to the geothermal heat. Duggan et al. (2007) concluded that geothermal heat had a major influence on the distribution and composition of biotic communities.

Some studies have noted the special characteristics of plant communities in these environments (Grime, 2006; Jordan, 1985) but few have explored in detail the relationship between geothermal factors and their impact on vegetation. Van Manen and Reeves (2012) studied the response of *Kunzea ericoides* var. *microflora* to changes in ground temperature and the risk of invasive species in areas with lower ground temperatures. Burns (1997) looked at vegetation patterns near the Te Kopia steam field near Taupo and concluded that soil temperature had the greatest influence on vegetation composition and structure. Similarly, Given (1980) at Karapiti, Glime and Iwatsuki (1994) at Ponponyama (Japan), Sheppard (1971) at Yellowstone National Park (U.S.A.), and Broady, Given, Greenfield, and Thompson (1987) at Mt. Melbourne (Antarctica) found geothermal vegetation zonation to be closely related to soil temperature.

Soil temperature has fundamental effects on the abiotic and biotic processes influencing vegetation (Aalto, Roux, & Luoto, 2013; Chapin, 1983; Olefeldt, Turetsky, Crill, & McGuire, 2013; Saito, Kato, & Tang, 2009). Soil temperature is a critical factor controlling the physiological activity and growth of plants (Mellander, Bishop, & Lundmark, 2004), restricting root growth, reducing nutrient uptake (Paré, Bergeron, & Camiré, 1993), and root permeability and water uptake (Brar & Reynolds, 1996). Moreover, soil temperature influences soil moisture levels (Bond-Lamberty, Gower, Wang, Cyr, & Veldhuis, 2006), microbial function and productivity (Lukewille & Wright 1997; Pregitzer & King, 2005).

Geothermal heat signatures are linked to crustal geology and tectonic activities (Monzier et al., 1999). They are often unevenly distributed (Barbier, 2002) and may change with time (Khutorskoi & Polyak, 2014). The levels of soil heat, steam, and gaseous output vary (Legittimo & Martini, 1989; McGee, 1997) depending on geological structures and the depth of the magma chamber and the water table (Legittimo & Martini, 1989). The area of soil heat emissivity will depend on the amount of heat flowing (Hoang, 2010) and can create a hostile environment for plants. The impact on vegetation reflects its distance from a heat source point (Kershaw, 1985). It is widely agreed that the effect of soil heat, irrespective of its source, is a major determinant of vegetation growth around the world (Given, 1980; Howard, 1964; Stout et al., 1997).

Remote sensing of thermal infrared (TIR) radiation is commonly used to measure land surface temperature, its distribution and temporal variation (Coll et al., 2005; Srivastava, Majumdar, & Bhattacharya, 2009) and has often been used to detect geothermal activity (Allis, Nash, & Johnson, 1999; Lee, 1978). Remote sensing provides data with a wide coverage of the area of interest, which is especially useful for geothermal exploration and research given the scattered occurrence of surface features (Heasler, Jaworowski, & Foley, 2009; Seielstad & Queen, 2009; Watson, Lockwood, Newman, Anderson, & Garrott, 2008).

In addition, thermal infrared remote sensing has been applied to the classification and long-term monitoring of geothermal ecosystems, (Mongillo, 1994; Seielstad & Queen, 2009) with research indicating a negative correlation between land surface temperature and vegetation (Goward, Cruickshanks, & Hope, 1985; Mostovoy, Anantharaj, King, & Filippova, 2008; Prihodko & Goward, 1997). Increasing emphasis has been placed on understanding this relationship (Li, Wang, Wang, Ma, & Zhang, 2009; Petropoulos, Griffiths, & Kalivas, 2014).

3.2 Methods

This study aims to use GIS and remote sensing techniques to assess variations in the spatial distribution of *Kunzea tenuicaulis* from historical aerial photographs taken in different years. The spatial distribution change pattern was compared with the changes in geothermal heat signatures seen in the TIR imagery, demonstrating the level of change driven by the ground heating caused by geothermal features. The level of impact caused by the geothermal ground heating also provided an insight of the influence climate change could have on vegetation.

3.2.1 Study area

The Taupo Volcanic Zone (TVZ) is an area of intense geothermal activity in the North Island of New Zealand (Kissling & Weir, 2005; Soengkono, 1995). It covers an area approximately 30 kilometres wide by 150 kilometres long and contains 23 geothermal fields or systems (Bibby et al., 1995). The structural association of TVZ geothermal fields was examined by Wood (1995) who concluded that the majority of the fields were located at the margins of major volcanic craters. The TVZ contains all but one of New Zealand's 24 geothermal systems (Heise et al., 2007). The 23 geothermal systems identified within the TVZ (Bibby et al., 1995) have different heat output (Kissling & Weir, 2005), ranging from <1 MW (Motuoapa geothermal system) to 540 MW (Waiotapu geothermal system) (Bibby et al., 1995).

Each geothermal field is typically 5 to 25 km^2 in area (Bibby et al., 1995) and it has been noted that the TVZ geothermal systems appear to be regularly spaced, with an average separation of about 15 km (McNabb, 1992; Wooding, 1976). Due to its suitability for power generation, the TVZ has received previous attention by investors (Brown & Simmons, 2003; Krupp & Seward, 1987; Wilson et al., 2007). Based on geology, Grindley et al. (1965) estimate the age of Wairakei-Tauhara geothermal field to be around 0.5 Ma at a minimum. The Wairakei-Tauhara geothermal field appears to have maintained activity during recent volcanism (Simmons et al., 1993) and has the largest observed heat flows in the TVZ (Kissling & Weir, 2005).

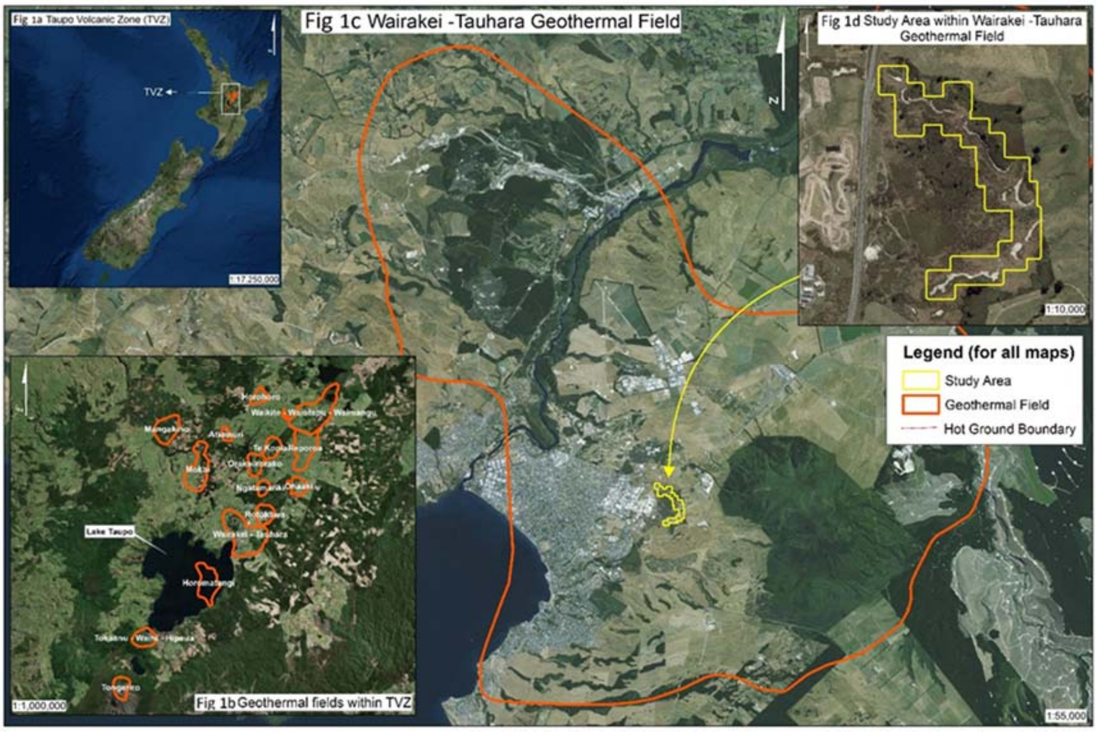


Figure 6. Taupo Volcanic Zone - geothermal fields. (Data source: Waikato Regional Council and Taupo District Council). (a) Location of the TVZ in New Zealand. (b) geothermal fields in the TVZ. (c) The Wairakei - Tauhara geothermal field, the hot ground boundaries allocated by Taupo District Council and the study site. (d) Aerial photo of the study area.

The section of Wairakei-Tauhara geothermal field covered by this study (Figure 6) is referred to as the Crown Road geothermal area, covering an area of about 1km^2. This ‘horseshoe ’shape of geothermal features with hot spots and a heated ground area is known for its steaming ground. It is protected against commercial development and owned by the Tauhara Middle 15 Trust who have consented to the conduct of this study on their land.

3.2.2 Study species

The dominant plant species found in the study area is ‘‘prostrate kanuka’’ or ‘‘geothermal kanuka’’ (Figures 7a, 7b). This plant belongs to the native tea tree genus *Kunzea*. While previously referred to as *Kunzea ericoides* var. *microflora*, in publications on geothermal vegetation (Honjo & Takakura, 1991; Moyersoen & Beever, 2004; Moyersoen, Beever, & Martin, 2003; van Manen & Reeves, 2012), a recent revision of the *Kunzea ericoides* (Myrtaceae) complex by de Lange (2014) recognises ten species, all endemic to New Zealand, seven of which are new species. The revised species of *Kunzea* found around geothermal areas is *Kunzea tenuicaulis* (de Lange, 2014) and is recognised by "a combination of growth habitat, branchlet hair and floral characters, supplemented by cytological and molecular differences" as detailed in de Lange (de Lange, 2014; de Lange, Datson, Murray, & Toelken, 2005; de Lange & Murray, 2004; Murry, de Lange , & Ferguson, 2005). The New Zealand Threat Classification System (Townsend et al., 2008) recognises *Kunzea* as a species under risk due to distribution confined to the active geothermal areas of the TVZ (van Manen & Reeves, 2012).

Figure 7. Photographs showing prostrate kanuka. (a) The distribution of prostrate kanuka around a feature surface feature. (b) A close-up view.

3.2.3 Aerial photographs

We analysed aerial photographs from 1975, 1985, 1999, 2002, 2008, 2012 and 2016 (Table 4). These were the only flights that had covered the study area. They consisted of a combination of black-and-white and colour imagery. The original 1975 and 1985 aerial photographs were taken on film cameras and had to be scanned and geoprocessed; all other aerial photographs were available in digital formats. All aerial photographs had different spatial resolutions. The spatial resolution of each photograph was related to the altitude, focal length and resolution of the camera (Borra-Serrano, Peña, Torres-Sánchez, Mesas-Carrascosa, & López-Granados, 2015) and resolution improved with advances in camera technology. All of the aerial photographs were captured in the summer months to reduce the effects of the sun's shadows. In summer, the sun is at its highest peak in the sky, and therefore the shadows were small. Imagery taken at other times of the year would have had large areas of darkness and the images would have been unclear.

Table 4. Availability of aerial photographs for the study areas at the Crown Road geothermal area. Images of different types and scales were available from different time periods and sources.

Time period	Image type	Scale	Source
1975	Black and white photo	1:25,000	Crown
1985	Black and white photo	1: 10,000	Crown
1999	Black and white photo	135 cm pixels	Taupo District Council
2002	Colour photo	100 cm pixels	Taupo District Council
2008	Colour photo	50 cm pixels	Taupo District Council
2012	Colour photo	12.5 cm pixels	Taupo District Council
2016	Colour photo	10 cm pixels	Taupo District Council

To standardise classification across resolutions from different images, we resampled 1999, 2002 and 2008 images to a common 13.5cm resolution using the nearest-neighbour methodology and we resampled 2012 and 2016 images to a common 12.5cm.

Following the procedure described by Laliberte et al. (2010), we then applied a 3 × 3 kernel low-pass filter to reduce spatial frequency. Resampling was introduced to improve the amount of information that could be extracted from imagery (Oleson et al. 1995), but in this case, the images were degraded or down-sampled (Sachs, 2001) to simulate pixel resolutions of the earliest imagery used in this study. Aerial photos provide continuous data. Each pixel represents the response of a region of the sensor to the light directed at it. As that light varies, the response also continuously varies. Resampling for this study used Python programming language. Using and interpolation technique. The tool (Figure 8) down-sampled 2002, 2008 and 2012 imagery to match the resolution of 1999 using an interpolation technique. The tool can be run from within ArcGIS as a script, or from the command line by supplying the required input parameters at run time. The 1975 and 1985 aerial photographs were not included in the resampling. This was because the 1975 and 1985 images were scanned from original films and, the resolution of the digital copy was determined by the scanning resolution. Although the original resolution can be calculated using the scale, resampling would also need to take into account the resolution of the digital imagery

```
# Import arcpy module
import arcpy


# Local variables:
RGB_Image_2002_tif__2_ = "RGB_Image_2002.tif"
v2002 = "D:\\GIS_Files\\Data\\resample\\2002"
rgb_2008 = "rgb_2008"
v2008 = "D:\\GIS_Files\\Data\\resample\\2008"
RGB_Image_2012_tif = "RGB_Image_2012.tif"
v2012 = "D:\\GIS_Files\\Data\\resample\\2012"


# Process: Resample
arcpy.Resample_management(RGB_Image_2002_tif__2_, v2002, "RGB_Image_1999.tif",
 " INTERPOLATE")


# Process: Resample (2)
arcpy.Resample_management(rgb_2008, v2008, "RGB_Image_1999.tif", " INTERPOLATE ")
```

Figure 8. Python script used for resampling 2012, 2008 and 2002 aerial imagery to the resolution of 1999 imagery.

3.2.4 Changes in the vegetation pattern over time

To investigate changes in the spatial distribution of *Kunzea tenuicaulis* over time, aerial photographs were classified in ENVI 5.2 to extract the areas of *Kunzea tenuicaulis* that appeared in the aerial imagery of each year. The supervised classification workflow in ENVI was used to define training areas for different vegetation types and then classify the remaining areas using the maximum likelihood method. Images were then smoothed to remove specking before saving the classification images in vector (shapefiles) and raster formats. One classification set was used to identify vegetation in images from

1999, 2002, 2008, and another set for 2012 and 2016. The images from 1975 and 1985 were classified separately. Then, classified vector datasets were imported to ArcMap 10.3.1 for further analysis and display. Vegetation cover was compared across years and field validation was conducted to verify all known areas of *Kunzea tenuicaulis.* To mitigate any inconsistencies, field validation was conducted in the summer of 2015 at the same time of the year that the imagery was captured. Furthermore, linear regression analysis was used to test for the relationships between time and vegetation distribution. Statistical analyses and graphics were performed using R version 3.2.2. (R Core Team, 2015).

3.2.5 Changes in geothermal land surface temperature over time

The thermal infrared imagery from 2009 and 2014 was compared using ArcGIS 10.3. To display the variations between cooler and warmer temperatures, a percent clip linear stretch colour ramp was used to categorise pixels into ten intervals between the minimum and maximum values. The stretched renderer worked well where there was a large range of values to display, in imagery, aerial photographs or elevation models. The same colour ramp and stretch were used for both thermal rasters.

A local geothermal energy company who had been capturing thermal infrared imagery for their monitoring requirements since the 1980s provided the thermal infrared imagery. The high quality of data required for this comparative study restricted the use of thermal infrared imagery captured before 2009. There were also calibration issues caused by not knowing the specifications of cameras used to take the photographs. The thermal infrared remote sensing data obtained did not enable any further classification or estimation of the surface temperature. The thermal infrared imagery was captured at night to reduce the effects of sunlight on heat contrasts; the flights were scheduled in summer months for favourable flying conditions.

3.3 Results

3.3.1 Geothermal land surface temperature

In Figure 9, the thermal data collected from the Crown Road geothermal photographs clearly shows the geothermal footprints and surface heat dispersion. Geothermal features are evident by their deep red colour. Field validation indicated that these geothermal features are associated with steaming heated ground rather than heat discharged from geothermal springs or streams. The areas in yellow are warm despite an absence of features, with the level of soil heat emissions depending on the level of heat flowing (Hoang, 2010) and the distance from the heat source (Kershaw, 1985; Legittimo & Martini, 1989). The yellow to greenish areas emit low heat but are still above ambient surface temperatures. The 2009 and 2014 thermal datasets (Map 1, Figure 9) differ in that for 2009 the majority of the study area was within the mid to high surface temperature range, with only small patches of low surface temperature. In the 2014 TIR dataset, however (Map 2, Figure 9), the majority of the study area is within the mid to low surface temperature range, with relatively small patches of high surface temperature. Most importantly, steaming grounds as indicators of geothermal heat up flow (Ranalli & Rybach, 2005) has significantly (59 percent) reduced from 2009 to 2014.

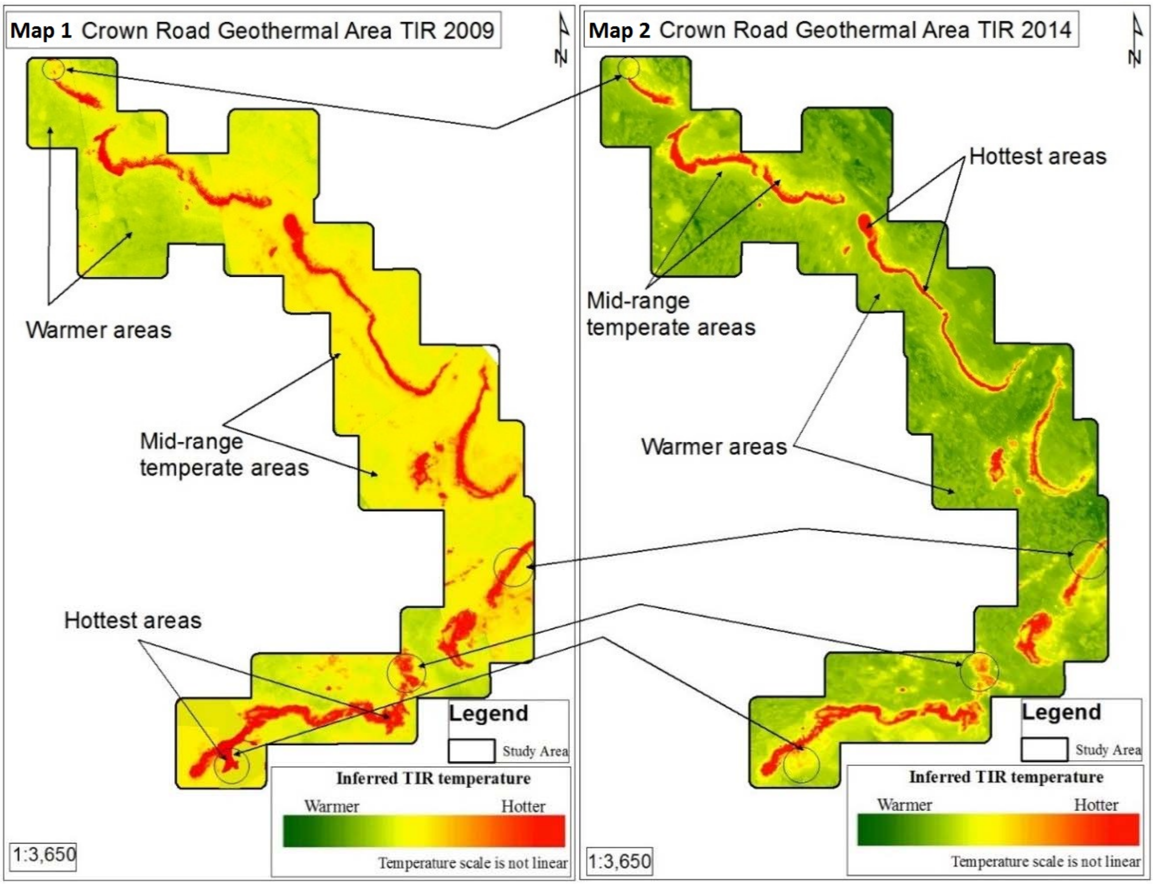


Figure 9 Variation in ground temperature at the Crown Road geothermal area in 2009 and 2014.

3.3.2 Changes in the spatial distribution of *Kunzea tenuicaulis* .

The distribution of *Kunzea tenuicaulis* varied from year to year. From 1999 to 2002, there was an increase in the extent of *Kunzea tenuicaulis* in the study area (Figures 10, 11). In the 2002 aerial imagery, the range of *Kunzea tenuicaulis* had not only expanded outwards from already established areas but had also spread to other geothermal areas where no *Kunzea tenuicaulis* was detected in 1999. From 1999 to 2002, there was a 20 % increase in the extent of *Kunzea tenuicaulis* in the study area. Between 2002 and 2008, *Kunzea tenuicaulis* extended to previously unpopulated sites. From 2002 to 2008, there was a 17 % increase in the extent of *Kunzea tenuicaulis*. From 2008 to 2012, there was a larger (70 %) increase in the extent of *Kunzea tenuicaulis* in established areas and at a few new sites.

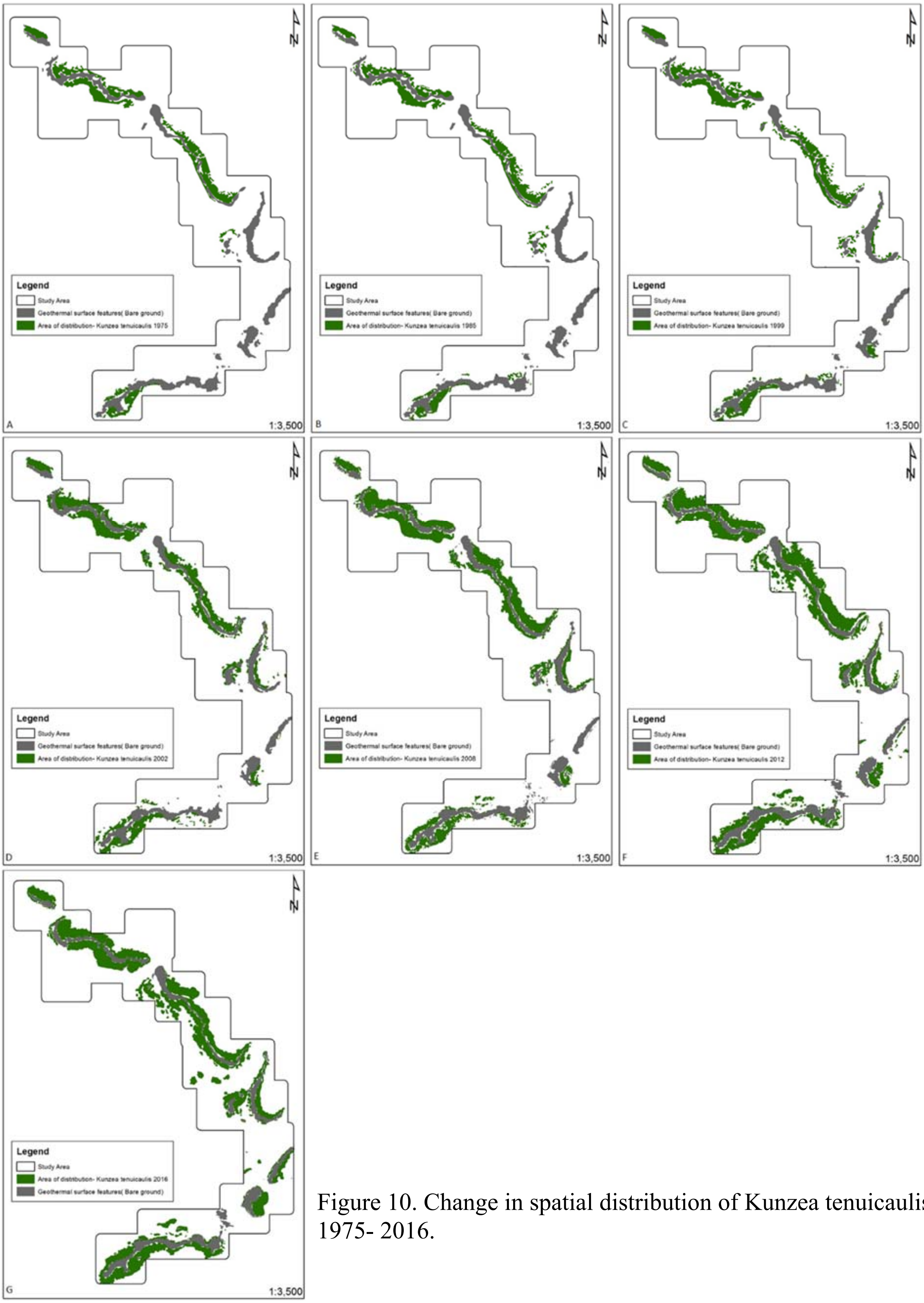


Figure 10. Change in spatial distribution of Kunzea tenuicaulis from 1975- 2016.

From 2012 to 2016, there was a 20 % increase in the extent of *Kunzea tenuicaulis*. A few new sites with *Kunzea tenuicaulis* were detected.

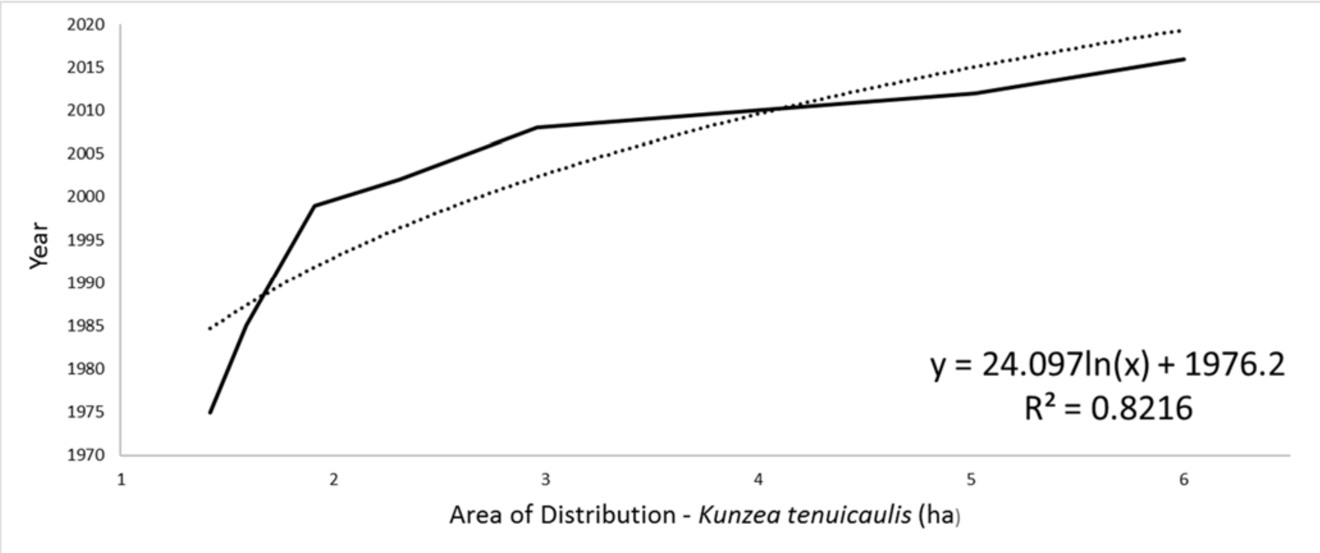


Figure 11. Increase in Distribution of Kunzea tenuicaulis, Crown Road geothermal area 1999-2016.

3.4 Discussion

Understanding long-term environmental change ideally requires studying a series of areas across time (Lishawa et al., 2013). Before the introduction of GIS, vegetation was mapped manually from aerial photographs (Dirzo & Garcia, 1992; Harrington & Sanderson, 1994), often for repeated surveys (Hastings & Turner, 1965; Meagher & Houston, 1999; Webb, Leake, & Turner, 2007; Zier & Baker, 2006). However, a chrono-sequence approach (Foster & Tilman, 2000) using aerial imagery and remotely sensed data analysed with Geographic Information Systems (GIS) technology (Hestir et al., 2008; Underwood, Ustin, & DiPietro, 2003) was a more pragmatic approach to this task (Springsteen, Loya, Liebig, & Hendrickson, 2010). The advantage of using aerial photography is that it provides a detailed, consistent and permanent time series which can be analysed by a range of independent and emerging technologies, producing analyses and highlighting variables in a rapid, systematic manner (Springsteen et al., 2010; van Manen & Reeves, 2012). However, the process has only recently been applied to the mapping of geothermal features and associated vegetation (van Manen & Reeves, 2012).

The review revealed that the spatial distribution of *Kunzea tenuicaulis* increased between from 1999 to 2012. A constant increase in the size of *Kunzea tenuicaulis* was demonstrated in every sequence of aerial imagery captured. This level of change in vegetation patterns and unexpected responses is a strong indicator of change in environmental variables (Cao & Woodward, 1998; Kaplan & New, 2006). In geothermal fields, vegetation establishment and growth is limited by several chemical and physical factors ad strongly controlled by the thermal gradient (Chiarucci, Calderisi, Casini, & Bonini, 2008), which is one of the most important parameters affecting land surface characteristics (Anderson et al., 2008; Brunsell & Gillies, 2003; Karnieli et al., 2010; Kustas & Anderson, 2009).

Furthermore, thermal infrared remote sensing data was used to show changes in the thermal characteristics of the study area. This was possible because the thermal contrasts between cold and hot land surfaces were high. Comparing thermal infrared remote sensing data between 2009 and 2014 revealed a significant drop in surface heat. Geothermal features maintain their shape but the area of high heat is reduced. The major change in surface heat is seen around the geothermal features, the majority of the mid-temperate areas are now within the warm temperature range.

The reduction in geothermal surface heat and *Kunzea tenuicaulis* distribution shows a negative correlation. This strongly suggests that the change in the geothermal heat and reduction in land surface temperature over the study area is increasing *Kunzea tenuicaulis.* A decrease in the land surface temperature (LST), leads to favourable soil conditions, thus allowing *Kunzea tenuicaulis* to thrive. A change in the LST will assist the increase of soil respiration rates (Kirschbaum, 1995; Lloyd & Taylor, 1994) reflecting changes in various soil biological properties. A reduction in LST will also assist in soil moisture retention (Calow, 2009). Furthermore, because soil moisture directly limits the rate of Nitrogen mineralisation, with better soil moisture retention, the soil in the study area will have more Nitrogen for uptake by vegetation during the growing season (Arndal et al., 2009; Nadelhoffer & Raich, 1992). The drop in LST did not lead to an ambient temperature level but did bring the temperature to a more tolerable range allowing *Kunzea tenuicaulis* to increase in distribution, signalling vegetation intensification and growth (Gandiwa, 2014; Gopal, Nagendra, & Manthey, 2015).The drop in LST was gradual and progressive between 1999 to 2012 and the increase in the distribution and density of *Kunzea tenuicaulis* that followed enabled an uninterrupted upward trend without any stress or damaging effects (Lichtenthaler, 1996). The adverse ecological effects of temperature on vegetation have been noted by many researchers (Pietruszka & Lewicka, 2007; Tottingham, 1923; Went, 1953).

Understanding the trends of *Kunzea tenuicaulis* and geothermal LST in the years the period of this study did not cover would have provided a richer understanding of long-term effects. Aerial photographs of the study site were obtained from the local council and since the study site is on the outskirts of Taupo town centre, it was not always covered in the local council's aerial imagery capture scope. In addition, regular thermal infrared data capture is not common because of its cost and limited use. This has led to the introduction of, unconventional methods of thermal infrared data capture (Nishar et al., 2016b). Currently, in New Zealand, aerial thermal infrared imagery standards do not exist. An imagery capture standard will provide a minimum data specification, promoting a high quality of data capture.

Furthermore, geothermal land surface heating simulates warming conditions (Chapin 1983; Clark & Roswall, 1981; Houghton et al., 1995; Houghton, 1996; Jonasson &

Shaver, 1999; Koch & Roy, 1995). At present, various climate change models are used to investigate the impact of warming (Canadell et al., 2007; Franchito & Rao, 1992). Over the years, these models have become better and more reliable (Busuioc, Chen, & Hellström, 2001). However, predictions of warming based on such models largely ignore climate-ecosystem interactions (Lashof, DeAngelo, Saleska and, & Harte, 1997) and limit the ability to simulate warming in smaller areas (Moraes, Franchito, & Rao, 2005; Sato et al., 2007). Geothermal land surface heating, as a simulation incorporates climate-ecosystem interactions previously ignored (Lashof et al., 1997). Singular units of geothermal hotspots are localised (Bhattacharyya & Leu, 1975; Teufel, 1987) and provide an ideal study area to enable the simulation of warming in smaller areas. Geothermal land surface heating has been naturally occurring for a long time (Browne, 1979; Grindley et al., 1965; Richmond, 1977; White, 1974) and as a result, establishing warming predictions on their characteristics, has a higher degree of reliability. We know that with warming the vegetation community will go through changes and this study assists comprehension of the level of change that could be expected.

3.5 Conclusion

Geothermal areas are of great economic and geological importance. Despite exposure to tough environmental conditions, they are sensitive to alterations in the unique physical and chemical characteristics of geothermal ecosystems. Although much is known about the response of plants to the direct effects of surface temperature, the use of a time series aerial and thermal infrared enables comparisons between surface temperature changes and plant growth through altering soil condition. The aerial and thermal infrared capture programs in New Zealand are driven by corporation organisations. Therefore, coverage and flights are not constant. Regular data capture will not only improve our understanding of environmental changes but also help to mitigate future changes.

This study has provided an insight into the impact of land surface temperature on vegetation. When associated with climate change, the results could ultimately provide insights into the complex interactions between changes in temperature and vegetation cover. Knowing the effects of fluctuating land surface temperature can be used to identify areas of potential vulnerability and then, the implementation of precautionary measures.

Characterising and mapping land cover is essential for modelling and understanding the distribution of vegetation. Remote sensing and digital image processing enable the observation, identification, mapping, assessment, and monitoring of distribution of vegetation at a range of spatial, temporal, and thematic scales. However, this will depend on the availability of data. The next chapter demonstrates the use of unconventional methods of data collection and processing while establishing the current thermal characteristics of the geothermal field. The introduction and utilisation of unconventional techniques such as UAV in the next chapter provide more options for data collection as UAV is more accommodating to small budgets and short timeframes. This process encourages sufficient temporal frequency (i.e. seasonal/bi-annual/annual) while maintaining a high quality of data collection to support monitoring efforts.

Chapter 4

Thermal infrared imaging of geothermal environments by an

Unmanned Aerial Vehicle (UAV)

Objective 2: Establish thermal characteristics of the Wairakei-Tauhara geothermal field using an Unmanned Aerial Vehicle (UAV)

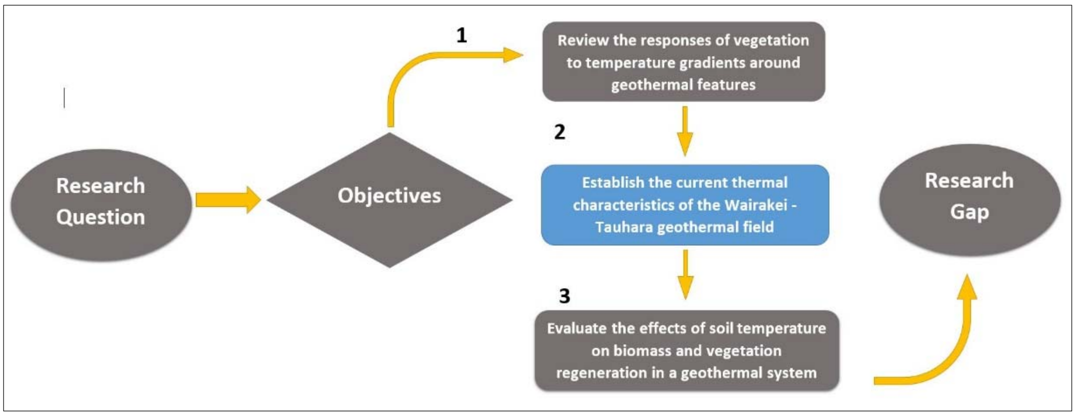


Figure 12. Objective 2.

A version of this chapter has been published as;

Nishar, A., Richards, S., Breen, D., Robertson, J., Breen, B. (2016a) Thermal infrared imaging of geothermal environments and by an unmanned aerial vehicle (UAV): A case study of the Wairakei-Tauhara geothermal field, Taupo, New Zealand. Renewable Energy 86, 1256-1264.

Nishar, A., Richards, S., Breen, D., Robertson, J., Breen, B. (2016b) Thermal infrared imaging of geothermal environments by UAV (Unmanned aerial vehicles). Journal of Unmanned Vehicle Systems.

Recent advances in unmanned aerial vehicles (UAVs) for civilian use make it possible to regularly monitor geothermal environments at spatial and temporal scales that would be difficult to achieve using conventional methods. Previous aerial monitoring of geothermal environments has been expensive and time-consuming. This study demonstrates the use of a small (<2 kg), cost effective quadcopter UAV to safely and accurately map physical and biological characteristics of these unique habitats. Thermal infrared imaging and photogrammetry are used to capture detailed information about geothermal surface features and surrounding vegetation within the Wairakei-Tauhara geothermal field near Taupo, New Zealand. The chapter highlights advanced techniques in sampling, processing and analysing UAV images and identifies some research challenges and limitations in the use of UAV platforms and sensors. The application of UAVs to describe and monitor geothermal features and other environments is a rapidly developing field in science and natural resource management. This study demonstrates the utility of UAV applications in geothermal science and the potential for their use in many other areas of research.

4.1 Introduction

Geothermal systems occur in regions of high subsurface heat flow related to hot rock located deep in the earth's crust (DiPippo, 2005; Rybach, 1981). Geothermal heat trapped in fluid-filled fractures and permeable rocks have been used for both domestic and commercial practices. In New Zealand, geothermal systems were used for heating and cooking by Māori for centuries (Bargh, 2012; van Manen & Reeves, 2012). Geothermal energy has also been used for electricity generation with the first geothermal power plant commissioned in New Zealand at Wairakei in 1958 (Daysh & Chrisp, 2009; Thain & Carey, 2009).

Around the world, geothermal energy accounts for a significant proportion of power production (Fridleifsson et al., 2008; Lund, 2006). The Central North Island contains all but one of New Zealand's geothermal systems generating 10% of New Zealand's electricity supplies (Bertani, 2012). Geothermal energy is a cost-effective, renewable source of energy with minimal carbon outputs, unlike coal burning power stations.

There is, therefore, global interest in geothermal power and there are increasing efforts to explore and characterise geothermal resources (Haselwimmer & Prakash, 2013).

Hochstein (1990) has described geothermal systems as convective water in the upper crust of the Earth that transfers heat to the surface of the Earth's crust. A geothermal system is made up of three main elements: a heat source, a reservoir and fluid that transfers the heat (Dickson & Fanelli, 1994). Elevated geothermal heat is usually transferred to the surface by the convection of ground water (Helgeson, 1968; Reiter, Shearer, & Edwards, 1978; Renner, White, & Williams, 1975). Heat may emerge at the surface as hot springs, fumaroles, mud pools and geysers (Heasler et al., 2009). However, geothermal systems may lack obvious surface features and are referred to as surface blind geothermal systems. In these cases, impermeable layers limit the continuous flow of hot fluids and gases to the surface (Hanson, Oze, & Horton, 2014) and can be difficult to identify. Despite this, these blind features have the same level of significance as the surface features for geothermal resource assessment and utilisation.

It has been recognised since the 1970s that aerial thermal infrared surveys (TIR) can be used to monitor both known and blind geothermal systems (Dickinson, 1973; Lee, 1978). While reflected data mainly provides spectral information on the surface characteristics of the landscape (Lynn, 1986), thermal infrared data provides additional spectral information on both surface and subsurface conditions (Chen & Campagna, 2009; Sabins & Lulla, 1987). The aerial TIR surveying method is applicable wherever there is a temperature difference in the environment (Johnson, Glenn, Burnett, Peterson, & Lucey, 2008). TIR imagery has been demonstrated to supply information which was previously a missing element in many fields (Stark, Smith, & Chen, 2014). The Wairakei and Tauhara geothermal fields were the first to be surveyed by TIR in New Zealand (Dickinson, 1973). Thermal imaging has since become a fundamental tool for geothermal monitoring (Mongillo, 1994; Mongillo & Bromley, 1992), with district councils regulating the geothermal fields requiring consent holders to conduct TIR surveys as part of their environmental monitoring programs. It is beneficial to collect TIR data over the area of interest at regular repeated intervals (Barber, Richard, Hochheim, & Orr, 1991; Johnson et al., 2008) to allow geothermal developers and resource managers to respond to changes in geothermal systems more proactively, rather than after adverse changes have occurred (Leroy, Anderson, Dykema, & Goody, 2008). The conventional practice of TIR aerial data collection is to use manned aircraft (Dickinson, 1973; Mongillo, 1994; Mongillo & Bromley, 1992), which is expensive due to the cost of the commissioned flight and the number of technical resources involved; thus influencing the frequency of the survey. However, this situation is unlikely to improve unless the costs associated with TIR data collection become more affordable.

UAVs are also sometimes referred to as UAS (Unmanned Airborne Systems) or even RPAS (Remotely Piloted Aerial Systems), and can be considered an alternative to manned aircraft. A UAV platform is capable of carrying different measuring devices (van Blyenburgh, 1999) and can be controlled manually by a trained person on the ground or flown autonomously according to a pre-programmed flight plan. UAVs were initially developed for military missions too difficult for manned aircraft (Tice, 1991). A variety of UAVs are available that can be employed for civil, industrial and agricultural research and management (Laliberte & Rango, 2011; Sullivan, Fulton, Shaw, & Bland, 2007; Yeh, 2011). Their size varies with the required payload, range and purpose (Altshuler, Yanovski, Wagner, & Bruckstein, 2008; Ambrosia et al., 2003; Casbeer, Kingston, Beard, & McLain, 2006; Kaaniche, Champion, Pégard, & Vasseur, 2005; Ollero & Merino, 2006), from as small as a bird to as large as a human piloted airplane (Eisenbeiss & Zürich, 2009).

In addition to their advantages in hazardous conditions, UAVs have other advantages including low cost, smaller dimensions, flexibility and the ability to reliably fly at low altitudes and around obstacles (Molchanov, Harmanny, de Wit, Egiazarian, & Astola, 2014; Ozdemir et al., 2014). UAVs are a tool that can complement other remote sensing technologies (Berni, Zarco-Tejada, Suarez, & Fereres, 2009) and are best suited to regional scale studies (Pinter Jr. et al., 2003). The processing and analysis of UAV data has been assisted significantly through recent advances in geographical information systems (GIS), mosaicking and image recognition (Mangiameli, Muscato, Mussumeci, & Milazzo, 2013; Venturi, Di Francesco, Materazzi, & Manciola, 2014).

The purpose of this chapter is to highlight the cost effective techniques for the collection of TIR imagery using an unmanned aerial vehicle (UAV) and an efficient workflow to process and analyse the data collected. This study also aims to demonstrate the high quality of output using this new methodology. The main motivation for employing the UAV was to precisely map the geothermal heat signature of a geothermal feature found in the Wairakei-Tauhara geothermal field, Taupo, New Zealand. Overall, the aim was to take advantage of a convenient and economical solution for TIR data collection, as opposed to contracting a costly and time-consuming staffed mission.

4.2 Wairakei-Tauhara geothermal system

The Taupo Volcanic Zone (TVZ) is an area of intense geothermal activity in the North Island of New Zealand (Kissling & Weir, 2005; Soengkono, 1995). It is an area approximately 30 kilometres wide by 150 kilometres long and contains 23 geothermal fields or systems (Bibby et al., 1995). The structures of the TVZ geothermal fields were examined by Wood (1995) who concluded that the majority were located at the margins of major volcanic craters. The TVZ contains all but one of New Zealand's geothermal systems (Heise et al., 2007). The 23 geothermal systems identified within the TVZ (Bibby et al., 1995) have different heat outputs (Kissling & Weir, 2005) but once formed, are stable and long-lived (Bibby et al, 1995).

Each geothermal field is typically 5 to 25 km^2 in area (Bibby et al., 1995). They appear to be regularly spaced, with an average separation of about 15 km (McNabb, 1992; Wooding, 1976). Drawing from geological data, Grindley et al. (1965) estimates the age of Wairakei-Tauhara geothermal field to be at least 0.5 million years old. The Wairakei-Tauhara geothermal field appears to have maintained activity during recent volcanism (Simmons et al., 1993), and has the largest observed heat flows in the TVZ (Kissling & Weir, 2005).

Due to its suitability for power generation, the TVZ has received previous attention by investors (Brown & Simmons, 2003; Krupp & Seward, 1987; Wilson et al., 2007). The TVZ has a high heat flow, and Hochstein (1995) gives a figure of 2600 MWe heat flow in the 100 km^2 area within the TVZ. There are currently five fields within the TVZ used for geothermal electricity with a generation capacity of about 750 MWe.

Despite the challenging environments, the Wairakei-Tauhara geothermal field supports a unique ecosystem. The survival of life near such high temperatures, has inspired studies by many researchers (Bott & Brock, 1969; Brock, 1967; Brock & Darland, 1970; Corliss & Dymond, 1979; Davis, 1897) and has attracted a strong ecological interest (Barnes et al., 1994; Pace, 1991; Reysenbach et al., 2000) in the Wairakei-Tauhara geothermal field. The plant species that are found and grow in the geothermal fields are often rare, and some are even endemic to this ecosystem (Burns, 1997; Given, 1980).

As the Wairakei-Tauhara geothermal field covers such a wide area, the local council has divided the field into hot ground boundaries based on the surface manifestations. A section of a surface manifestation within the largest hot ground boundary was selected for this study. The site lies within a geothermal reservation area and is protected against any commercial developments. It is owned by the Tauhara Middle 15 Trust who have consented to this study being conducting on their land. Figure 6 (Chapter 3, p. 31) indicates the extent of the TVZ, the Wairakei - Tauhara geothermal field and the study area.

4.3 Materials and methods

4.3.1 Platform

Geothermal areas present a unique environmental and geographic challenge. The UAV must be able to take-off and land in rugged terrain. It must also be stable, capable of carrying a high-resolution camera, withstand steam and wind and remain light enough to be easily carried into the field by one person. All of the fixed-wing platforms were eliminated because of launch and recovery constraints of fixed-wing aircraft and the challenges faced by small fixed-wing aircraft in manoeuvring over and collecting high-resolution images and overlaps of small targets in moderate winds (Hodgson, Kelly, & Peel, 2013; Watts, Ambrosia, & Hinkley, 2012). The category of platforms that seemed to meet all of our criteria was the small multi-rotor, battery-powered vertical take-off and landing vehicle. These aircraft are easy and safe to operate, can hover over the target area during photographic operations, and can take off and land almost anywhere (Funaki & Hirasawa, 2008). Therefore, we selected the Blade 350 QX2 Quadcopter.

A Blade 350 QX2 Quadcopter with a Spektrum DX5e DSMX 5-Channel Transmitter by Horizon Hobby, LLC (Figure 13[a]) was used to fly over the study area. The UAV has GPS and compass functionality, weighs approximately 1kg including the battery and camera, has an eight to twelve minute flight time and a controlled maximum height of up to 45 metres in "smart" mode depending on the needs of the mission. The quadcopter has other flight modes for more experienced operators but for survey work, smart mode was used exclusively. The quadcopter also has an autonomous return home functionality, which can be engaged at any time or engages automatically if communication is lost. For this study, smart mode was used to reliably capture data with wind speeds of up to 20 km hr^{1}.

4.3.2 Camera and sensor

A Sony HDR-AS100V (Figure 13[b]) mounted below the quadcopter was used to capture colour (RGB) aerial images and a FLIR Tau 320 camera and sensor was used to capture thermal infrared videos. Table 4 lists the specifications for both devices. The Sony camera weighed 92 g, measured 24.2 mm x 46.5 mm x 81.5 mm and was enclosed in the supplied splash proof case. Geotagged images at 13.5-megapixel resolutions were captured at one-second capture intervals.

The FLIR unit used an FLIR Tau 320 sensor with an FLIR 25mm lens and Flashback 3 single recorder writing to a full-size SD card (Figure 13[c]). The unit was operated using its standard 8.3fps PAL video mode. The whole unit was mounted in a custom-made 2mm birch ply and carbon fibre case covered with aluminium foil to shield the UAV from RF noise. Power for the unit was taken from one cell (4 V nominal) from the voltage-balancing plug on the three-cell 11.1 V lithium polymer flight battery. The Tau 320 is also equipped with an FLIR Tau Photon Replicator Board, which communicates via a 30-pin SAMTEC connector and allows the use of voltage inputs between 6 and 27V.

Power comes from one cell operating off the balance plug on the flight battery. FLIR Tau 320 is capable of detecting wavelengths in the range of eight to fourteen microns. The camera is lightweight and has up to a 921600 Baud rate which allows quicker interaction with a computer or laptop (FLIR, 2010). The video files need to be downloaded from the camera to be viewed, as the camera does not come with a built-in preview screen. Lai, Kou, Poon, Tsang, and Lai (2010) and Tashan and Al-Mahaidi (2012) have successfully used FLIR Tau 320 cameras to address their research needs.

Table 5. Camera and sensor specifications for the Sony HDR-AS100V and the FLIR's Tau 320.

Sony POV Action Cam (HDR-AS100V)	**FLIR's Tau 320**
Lens Type : ZEISS Tessar	Thermal Imager : Uncooled VOx Microbolometer
Aperture: F2.8	FPA Formats 324 × 256
Focal Length : f=15.3 mm (170°), f=21.3 mm (120°)	Pixel Size : 25-micron
Minimum Focus Distance: Approx. 30cm	Full Frame Rate : 30 Hz (NTSC); 25 Hz (PAL)
Focal Distance: f=2.5 mm	Exportable Frame Rates : 7.5 Hz (NTSC); 8.3 Hz (PAL)
CCD Resolution: 13.5 megapixels	Input Power : 4.0 - 6.0 VDC
Dimensions: 1.8 by 0.95 by 3.2 inches	Power Dissipation : <1 W
Image Stabilization: Digital	Sensitivity : <50 mk f/1.0
Interface Ports: micro USB	Time to Image, FFC Interval : <3.5 sec, <0.5 sec
LCD size: 1 inches	Size : 1.75" × 1.75" × 1.18"
Mic Input Jack: Yes	Operating Temperature Range: -40°C to +80°C
Sensor Type: CMOS	Non-Operating Temperature Range : -55°C to +105°C
Still Image Mode: JPEG	Tau Lens Resolution: 320 × 240
Video Format : MPEG4-AVC/H.264	Tau Lens FOV (H x V): 18° × 14°
Waterproof Depth (Mfr. Rated):16.5 feet	Tau Lens f/# :1.1
Video Resolution:1080p	Tau Lens weight : 135g

Both of the cameras had wide angle lenses suitable for mounting to face directly downward on a UVA to capture data over a reasonably flat study site (Mastor, Sulaiman, Juhari, & Samad, 2014). The Sony HDR-AS100V is a shockproof action camera that is fitted with a built-in image stabilisation function (VillasBoas, 2014) to reduce the effects of sudden movement and vibration. The FLIR Tau 320 sensor is built to endure shock up to 200g shock w/11 mSec (Glenn, 2011), which provides sufficient tolerance to sudden movements while in the air.

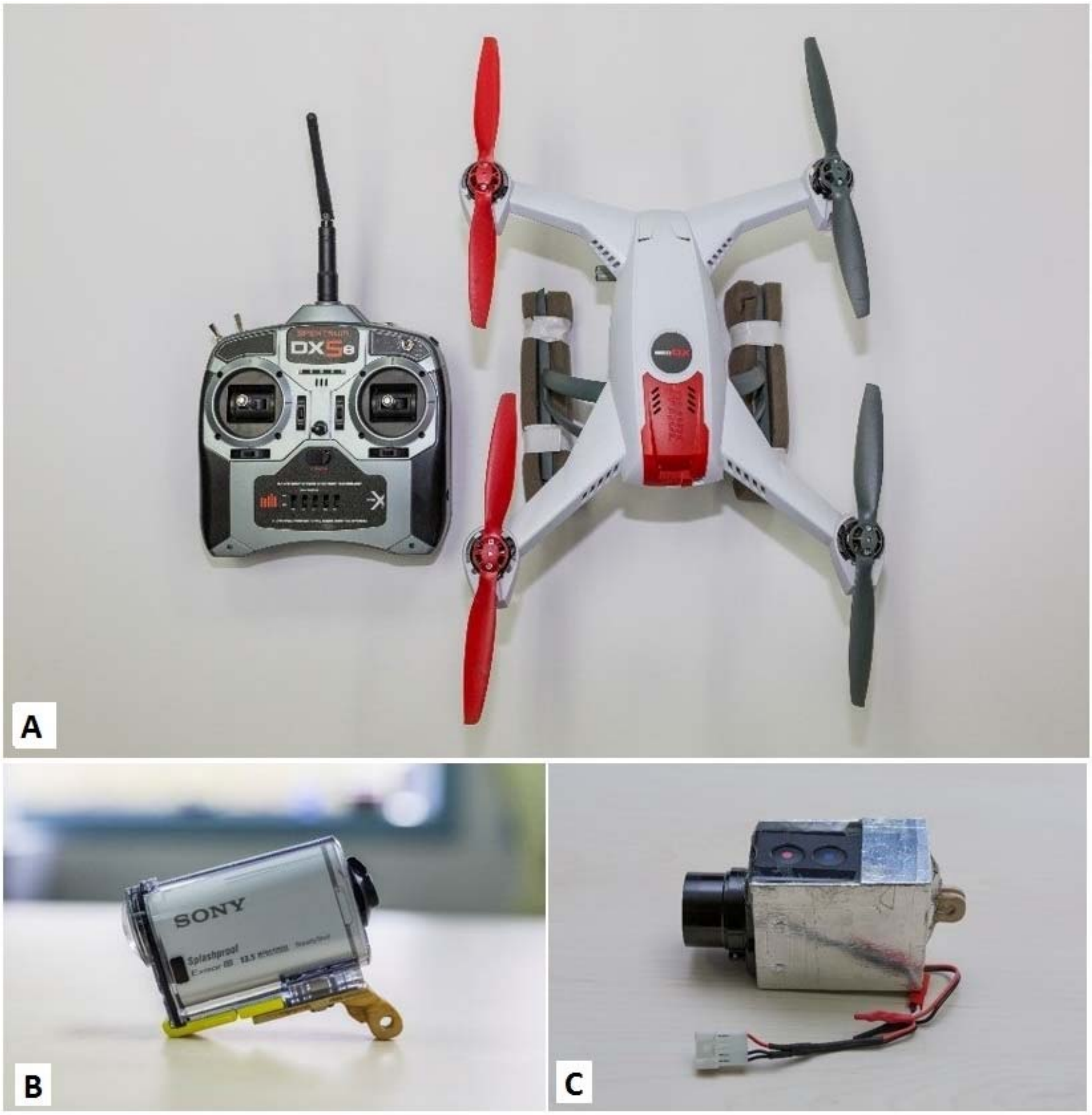


Figure 13. Drone and cameras used in this study. (a) Blade 350 QX2 Quadcopter with a Spektrum DX5e DSMX 5-Channel transmitter. (b) Sony HDR-AS100V action camera. (c) FLIR Tau 320 sensor covered with aluminium foil.

4.3.3 Image acquisition

To geo-reference UAV imagery in the absence of precise navigation data, Ground Control Points (GCP) are required. For optical images, natural GCPs are the norm. However, in many cases, it is not possible to find natural GCPs in thermal images that appear sufficiently crisp and can be located accurately. Thus, I decided to use artificial GCPs. I used aluminium as the material for the GCPs. Five control points (30cm paper plates covered with aluminium foil; Figure 14.) were arranged within the study area as aluminium sheets have a sharp boundary in a thermal image (Ross, 2013).

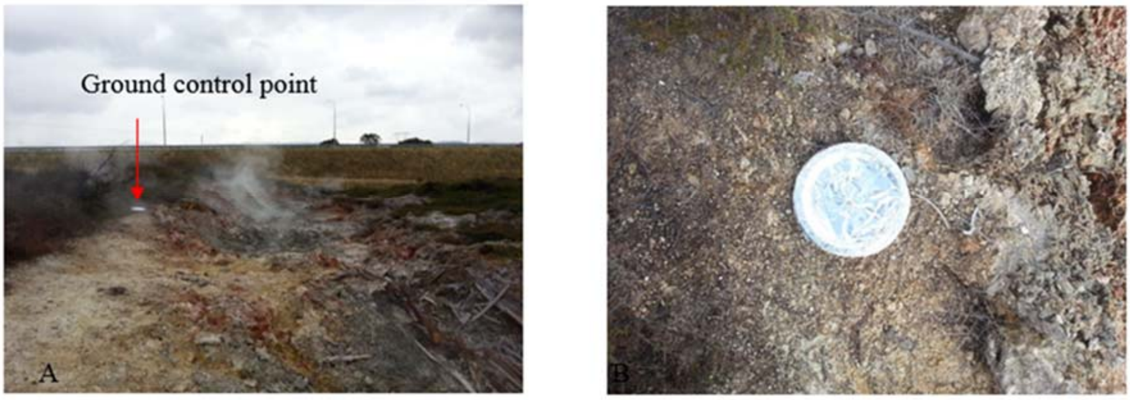


Figure 14. Picnic plates covered with aluminium foil used as ground control points.

The 700m^2 study area was flown separately with the colour camera and then later with the thermal infrared camera. Although the UAV is capable of flying in light rain and windy conditions, the high risk posed to the sensors and aircraft's performance meant that this was not done. Wind speed and rain forecast were checked on the metrological services website before all flights. Those wind speeds up to 20km/h were within the safe operation procedures. This standard was strictly followed because of concerns that strong wind could hinder the stability of the drone and affect the image quality. Furthermore, strong winds made landing in dusk light much more complicated and uncertain. To reduce the impact of solar radiation, flights occurred at dusk. While it is preferable to capture thermal infrared data at night, New Zealand Civil Aviation regulations (https://www.caa.govt.nz) do not permit the use of UAVs at night. Due to the time window and necessary levels of overlap, thermal data was captured on eight separate occasions.

To obtain high-resolution thermal infrared images and sufficient overlapping images, the quadcopter was flown at a slow speed at an altitude of 20 meters repeatedly across the study site (Figure 15[a]), taking photographs every one-second. To acquire images with sufficient overlap, the UAV was flown along both the long and short axes of the study area (Figure 15[b]).

Geo-tagged colour aerial images were captured showing the GCPs to use for geo-referencing. For the capture of colour images, two flight missions were carried out between 11am and 2pm on each flight to minimise the influence of shadows on the imagery. Figure 15 shows the flight path followed to collect colour aerial imagery. The same flying procedure was followed, only the flight time and overlap requirements differed between colour missions and thermal infrared missions.

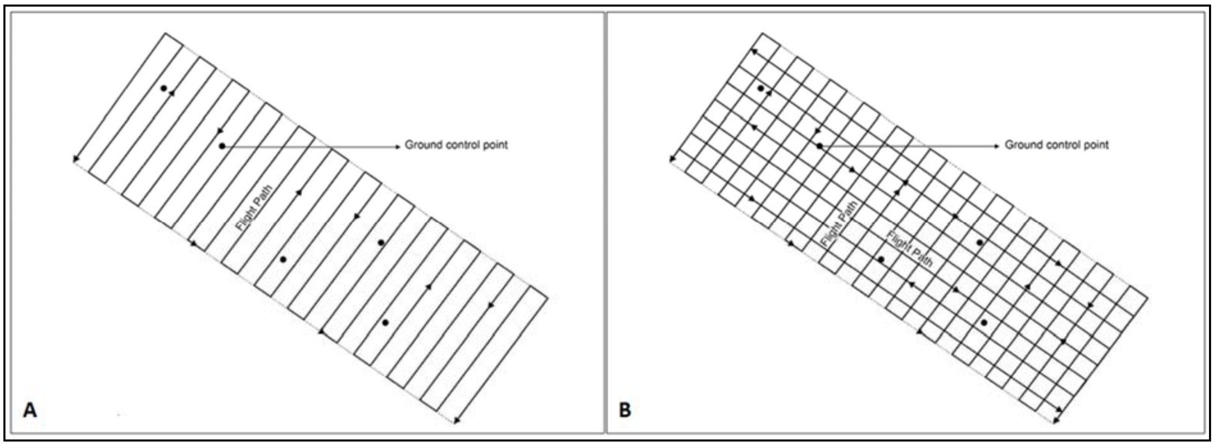


Figure 15. (a) Planned flight path for colour aerial image capture and the positions of control points. (b) Planned flight path for thermal infrared video capture and the positions of control points.

4.3.4 Image processing

Colour Aerial Image Processing

Over 1700 colour (RGB) images were captured. Each image was approximately 1.2MB in size and 1920 x 1980 in dimension and was associated with a .xml file containing georeferencing data. Images were calibrated and ortho-mosaiced into one image of the entire study area using Pix4D (http://pix4d.com). At the time of the study, two supported UAV Image processing software packages dominated the market, Agisoft

PhotoScan and Pix4D. Pix4D was chosen due to its regularly updated and comprehensive camera database, excellent technical support, good collection of documentation and increased options for outputting data.

During the 2010 earthquake recovery in Haiti, Pix4D was used by the International Organisation for Migration and United Nations Operational Satellite Application programme to produce the overview mosaic and elevation model for the topographical and hydrographical studies (Zhang, 2014). Strecha, Fletcher, Lechner, Erskine, and Fua (2012) also demonstrated the capability of UVAs with Pix4D software to develop species-specific vegetation maps in Australia.

The Pix4D applies computer-visioning theory to compare conjugate points in overlapping images and determine their relative positions and orientations by bundle block adjustment (Bollard Breen et al., 2014). In similar systems, about 20 key points per image are selected for matching but the Pix4D uses up to 60,000 points. The software adjusts for focal length and lens distortion and the position and attitude of the camera. It also uses the relative views of neighbouring images to create a digital terrain model (DTM) with 3-D coordinates for each image pixel (Bollard Breen et al., 2014). The model is refined and positioned using independent georeferencing data and ground control points collected by GPS.

The Pix4D can be run on a PC workstation but we chose to use Amazon cloud computing because of the number of images and amount of processing required. Amazon Cloud Computing (Amazon EC2) provides a range of computer capacities made available as virtual servers (Table 6 lists the specifications of the cloud computer used). Subsequent spatial and image analyses were processed in ArcGIS 10.2.

Table 6. Description of the cloud computer used.

Cloud Compter used:
Windows 8, Server 2012, 64 bits
16 CPU
32 GB RAM, 10 GB HDD Free Space.

Thermal Infrared Aerial Image Processing

The FLIR Tau 320 unit captures grey scale video (.avi) without any geo-referenced data. Still frames were subsampled from the video using tools developed in the 'Python' program language. The tool was set to capture a still image at a rate of one per second from the video to provide 9,846 infrared, grey-scale images. The tool can be run from within ArcGIS as a script, or from the command line by supplying the required input parameters at run time.

The infrared images were mosaicked and modelled in Pix4D by the cloud computer in a process similar to that used for the colour images. However, the camera specifications had to be manually calibrated and the resulting mosaic was not geo-referenced. The infrared ortho-mosaic was geo-referenced in ArcGIS 10.2 using the GPS coordinates of the ground control points and then re-projected into the same coordinate system (Universal Transverse Mercator Zone 60S with World Geocentric System 1984 datum) as the colour mosaic.

4.4 Results

4.4.1 Colour aerial image

The colour ortho-rectified mosaic (Figure 16) has a pixel size of 1.8 cm. Because the optimal time of the day was chosen for flying, no shadows in the imagery were detected, and the integrity of the geothermal area was maintained. The mosaic displays the boundary of the geothermal surface manifestations clearly as bare ground with patches of white, grey and pink contours caused by geothermal heat and chemical discharge. The mosaic also shows the runoff channel caused during the last heavy rainfall. The vegetation surrounding the surface manifestations exhibits colours ranging from healthy green to brown and grey, which signified dead plants. The main purpose of the colour imagery was to provide the GCPs for geo-referencing the TIR imagery. The GCPs were easily identified and their coordinates were extracted (Table 7).

Table 7. Coordinates (NZTM) of the ground control points.

GCP	Easting	Northing
1	1870932.605	5713473.678
2	1870938.414	5713468.014
4	1870954.232	5713458.381
5	1870954.657	5713450.444
3	1870944.485	5713456.699

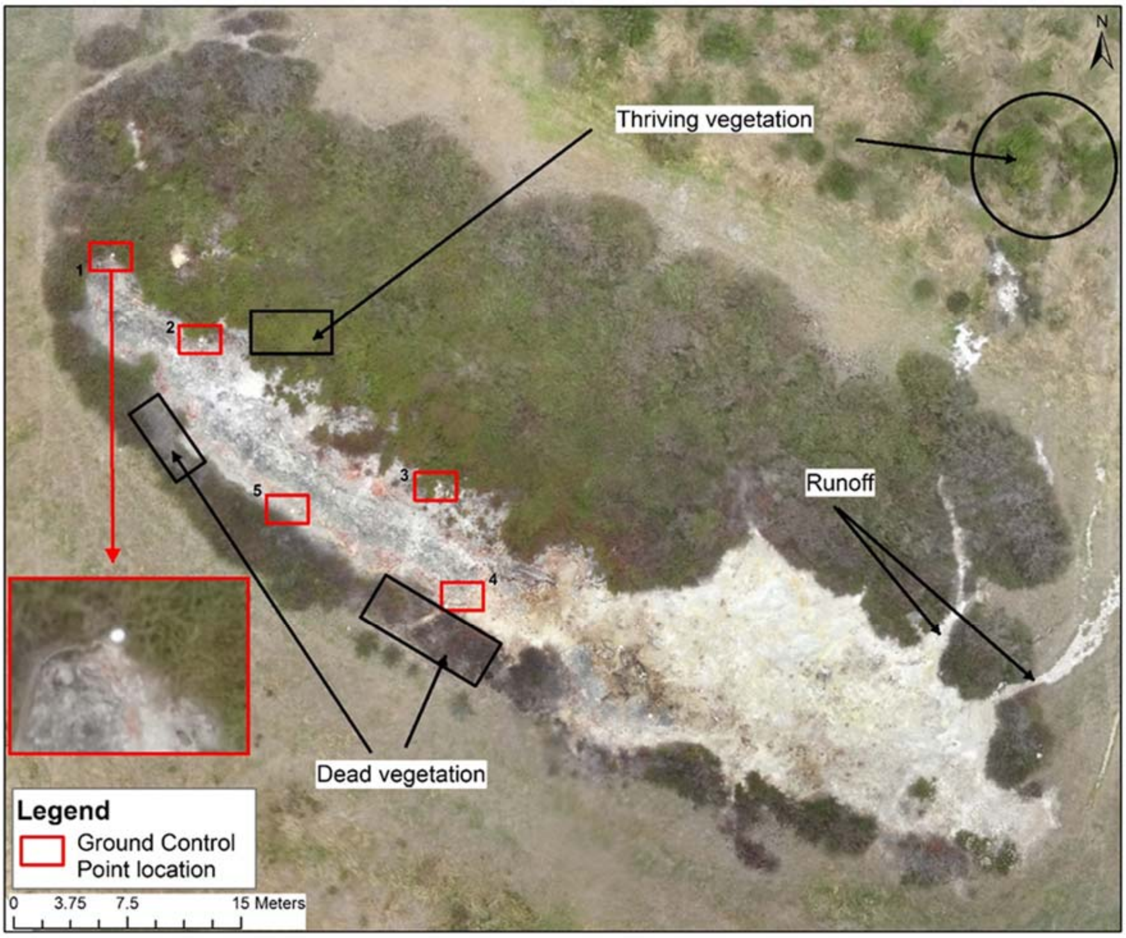


Figure 16. Colour aerial image of the study areas showing the thermal features, surroundings and controls points.

4.4.2 Thermal infrared aerial image

The ortho-mosaic of the thermal infrared imagery is shown in Figure 17. The orthorectified mosaic has a pixel size of 0.5cm, a significantly better resolution than in the colour mosaic. The colour scale is non-linear. It stretches subtle differences near inferred ambient temperatures and compresses inferred temperature differences at higher temperatures. A warm to hot thermal anomaly range was computed by normalising the values of the ortho-rectified mosaic.

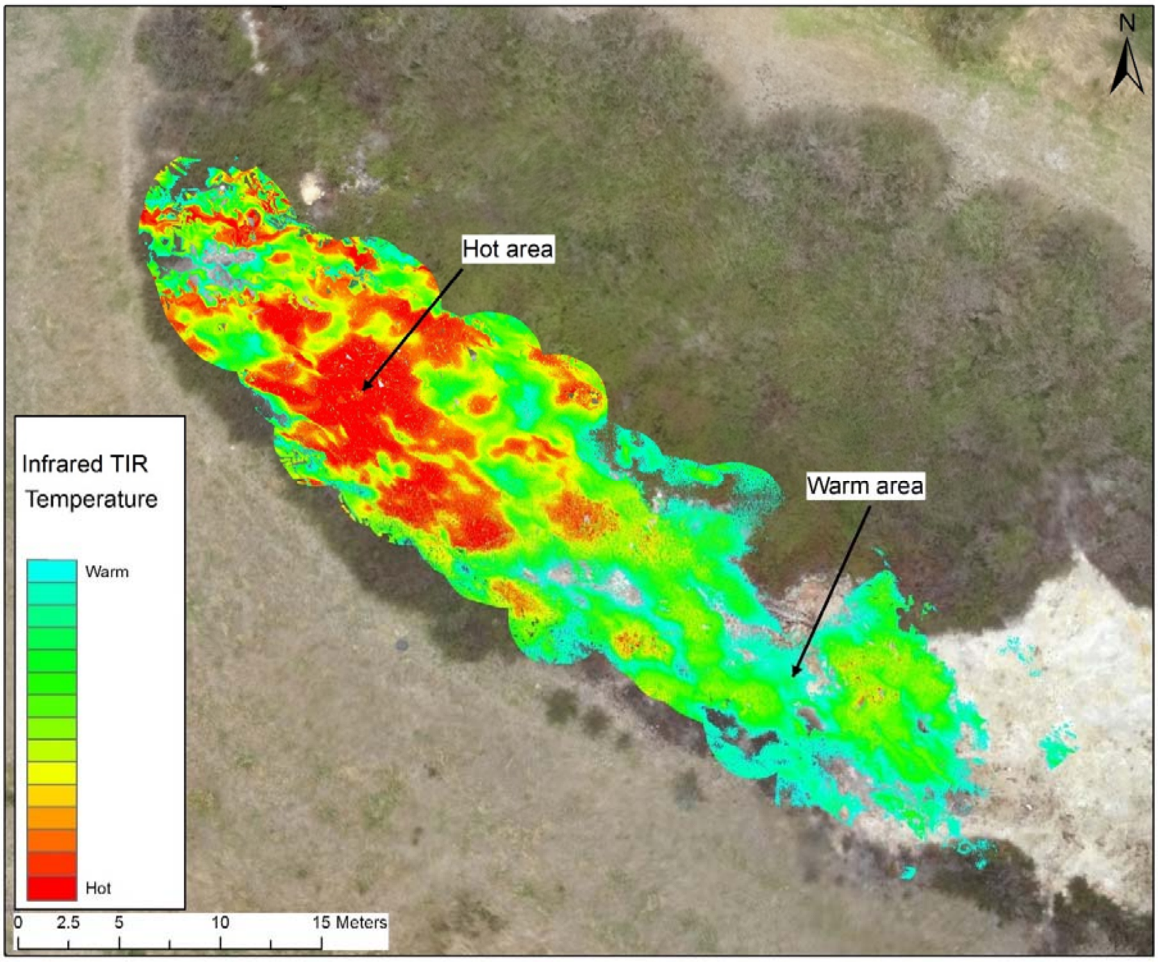


Figure 17. Thermal infrared aerial image of the study area's geothermal feature.

Numerous warm to hot thermal anomalies exist in the study area, and appear as hot bare ground. These features are associated with steam-heated ground rather than discharging geothermal springs or streams. The inferred TIR image shows that inferred high temperatures (red colour, temperatures >90°C) occur and dominate the west side of the surface manifestation, whereas the warm areas (green to blue colours, temperatures <50°C) can be seen toward the southeast end. Emphasis was given to collecting images with a high overlap, and the quality report from Pix4D application demonstrated that the study area had more than five overlapping images from the overlap score.

4.5 Discussion

Equipment specifications were the main consideration when choosing a suitable UAV platform and sensors for this study. The Blade 350 QX quadcopter was purchased for under $1000 NZD, could be easily used in a difficult-to-access environment, was light-weight and easy to transport over difficult terrain and had the functionality to carry out accurate aerial surveys. Its affordability permitted repeat surveys to detect change over time. By contrast, traditional aerial photography methods are limited because of the high cost of obtaining repeated imagery.

The thermal infrared image of the study area was successfully captured, processed and projected. The 0.5cm pixel size of thermal infrared mosaic is due to the quadcopter being able to fly at an elevation of 20m to capture data. The colour ortho-rectified mosaic has a pixel size of 1.8cm compared to the one obtained from Land Information New Zealand (http://www.linz.govt.nz), which had a pixel size of 20cm. The height of imagery capture is one of the major differences between the two sets of ortho-rectified mosaics.

There are cameras and sensors available for a variety of applications, but it is important to acknowledge the payload limit of the UAV, and the risk of poor performance as well as a potential loss of data quality (Brockers, Hummenberger, Weiss, & Matthies, 2014). The quadcopter used for this study successfully carried the 350 g FLIR Tau 320 camera, but heavier loads would result in reduced flight times and increased thermal loads on the motors and controllers.

One limitation of this inexpensive quadcopter and transmitter was the inability to set waypoints that would allow it to fly autonomously. The UAVs that offer waypoint navigation and autopilot options allow users to plan and programme flight paths, heights and speeds (Prats, Santamaria et al., 2013). This makes it easier to cover larger areas without losing battery time in manual manoeuvring. Without waypoint navigation, navigating a route to provide a suitable overlap between images has to be done visually, with the potential to leave gaps or sample unnecessarily. However, by manually planning routes carefully along equally spaced transects, most of these problems were avoided in this study. That said, this approach would be difficult and time consuming for larger survey areas.

Another limitation of using light small-sized UAVs is the lack of reliability to stay on a straight flight path or a fixed elevation, resulting in overlap variations and a difference in rotation angles between adjacent images (Remondino, Barazzetti, Nex, Scaioni, & Sarazzi, 2011). However, the Pix4D with a standard aerial triangulation procedure was suited for the orientation of images with irregular overlap acquired by UAVs (Ai et al., 2015). Applications, like Pix4D, automate the extraction of consistent and redundant sets of tie points from images captured by UAV (Laliberte, Herrick, Rango, & Winters, 2010; Pierrot-Deseilligny, De Luca, & Remondino, 2011). The Pix4D can accomplish a fully automated project, requiring only camera calibration parameters and the images as input. The Pix4D also automatically creates the points cloud, the DSM and the orthophoto. The post-processing matches points in overlapping images, which together create a mosaic. The entire post-processing is based on the values extracted from the images and the calibration of the camera (Küng et al., 2011) that limits the external sources of errors.

While many efforts have been directed towards developing UAV control systems, communication and navigation (Ozdemir et al., 2014) less attention has been paid to increasing the battery life for small UAVs to maximise their flight time (Suzuki, Kemper Filho, & Morrison, 2012). Current users overcome this challenge by carrying several charged batteries for replacement in the field. There are options under investigation, but not yet available in the market (Cwojdziński & Adamski, 2014; Saha et al., 2011).

It paid off to fly only in appropriate weather conditions. No flight was attempted in wind speed more than 20km/hr, for both the colour and thermal infrared imagery capture it was very important to maintain the stability of the UAV and this would not have been possible in high winds. It was also noticed during the test flights that high wind speed and opposing wind direction consumed batteries faster, thus shortening the flight time. For dusk-time flying, extra care had to be taken because there was reduced visibility. Flights were suspended each time the wind picked up speed or changed course. The colour imagery showed minimal shadows as shadows would have made it difficult to extract information (Sohn & Yun, 2008). TIR images were captured at dusk to reduce solar radiation and the outputs did not show any irregularities that would suggest solar interference.

Despite weather reports, conditions are unpredictable and can limit UAV operation. The high wind conditions experienced during this study had a great impact on UAV performance (Evers, Dollevoet, Barros, & Monsuur, 2014). Temperature, fog and rain can also impact a UAV mission (Sauter, 2007). The information on weather is crucial for UAV mission planning and execution, but the flight plan needs to be flexible to allow for weather circumstances. Considering the weather was important because not only could it challenge the UAV flight settings and sensor payload affecting the overall results, but it could also compromise the safety of the pilot and the onlookers. Obtaining enough overlaps of the images was key since the raw images were to be processed using Pix4D and the number of overlaps played a particularly important role in the quality of the final mosaic. In this study, we were able to obtain more than five overlaps per pixel, which contributed to a high-resolution mosaic but took a considerable time to complete. The whole mosaicking procedure for colour imagery lasted ten hours, while the TIR mosaicking procedure lasted up to twenty-five hours. Both procedures used a cloud computer, whereas the attempt on the desktop computer was still running after four days.

The FLIR Tau 320 was an appropriate thermal camera due to its small size (44.5 × 44.5 × 30.0mm), light weight, low power consumption and cost. The 25mm lens provided a flexible detection range suitable for use with a UAV without any waypoint navigation or autopilot option. It can be a challenge to maintain a consistent flight height when flying manually. The detection range offered by the 25mm lens allowed data to be reliably collected despite small variations in height.

It is current industry practice to capture GCP locations using a differential GPS unit (Jayaprasad, Narender, Pathan, & Ajai, 2008), but this study was limited by funds and the GCP locations had to be extracted from geotagged colour imagery. Colour imagery capture of the study areas at the same time as TIR imagery also allowed for correlations between visible and thermal features. For example, the high-temperature areas shown in the TIR imagery were seen as bare ground in the colour imagery.

The high interest in UAVs for civilian use (Drubin, 2013) has prompted civil aviation authorities around the world to impose controls, regulations (Drubin, 2013; GCAA, 2015; La Franchi, 2004; Vogel, 2014) and guidelines for appropriate use under certain conditions (Laurence, 2001; Roberts & Tayebi, 2013). Where there is a need to operate outside of regulations, it may be possible to request exemptions from local civil aviation authorities. Accordingly, one output of this research project is to provide recommendations about flying over geothermal areas to contribute to the development of appropriate guidelines and regulations.

Despite geothermal areas being protected from development, most still operate with public access. However, it is vital to limit public access while flying over geothermal areas. When conducting the study, it is important to have at least one other person involved apart from the flight operator to assist in keeping a watch for any ground or aerial hazards. Steam and hot water burns are a potential risk in geothermal features. Consequently, the UVA operator and all parties assisting should be wearing appropriate personal protective gear. Autonomous navigation systems (Brockers et al., 2014) make reliable, systematic sampling designs relatively simple for even relatively inexperienced operators. Improvements in these areas are matched by advances in data processing and analysis techniques capable of handling thousands of images and variables (Mesas-Carrascosa, Rumbao, Berrocal, & Porras, 2014).

To reduce the solar effects, TIR surveys are best flown at night (Mongillo, 1994). Due to the restriction imposed by the Civil Aviation Authority of New Zealand against flying UAVs after dark, TIR data was captured at dusk. The flying window was very short and multiple flights had to be planned and executed. With an increase in UAV applications for commercial, research and recreational use (Finn & Wright, 2012), regulations are necessary to protect the interest of all stakeholders. However, specialist research of the kind carried out in this study may be dependent on certain conditions and these requirements need to be taken into consideration. Aviation Authorities may need to look into the different applications of UAVs and regulate accordingly to allow for specialist use such as the capture of TIR data at night.

As improvements to platforms and the sensors continue to develop, the future of UAV research within the geothermal sector is likely to explore applications not yet considered. The paramount benefit of using UAV is a reduction in costs (Berni et al., 2009). The cost of the aeroplane, crew, fuel and camera involved in a traditional aerial survey (Visser, 1961) requires a significant budget compared to a UAV mission (Hoffer, Coopmans, Jensen, & Chen, 2014).

Furthermore, the increasing payloads of UAVs (Kim et al., 2013; Selinger, 2005) and the variety (Dziuban, Wojnar, Zolich, Cisek, & Szumiński, 2012) of small, lightweight (Aguasca, Acevo-Herrera, Broquetas, Mallorqui, & Fabregas, 2013) sensors offering a high level of precision and data accuracy (Haarbrink & Eisenbeiss, 2008) at low altitudes make these tools increasingly valuable. With geothermal environment rapidly changing (Bibby & Hurst, 1990), UAV monitoring can provide a time and cost efficient solution for regular data capture to investigate changes in surface heat signatures, vegetation, geothermal surface features and geothermal energy production asset inspection. With the appropriate sensor (Whitehead et al., 2014), the possibilities are endless for both full motion video and still image capture. The implication of UAVs does not have to be limited to geothermal monitoring. It can be replicated for mapping, feature detection and landform studies within any discipline.

4.6 Conclusion

This chapter has demonstrated the use of UAVs for thermal infrared data capture in the geothermal environment as well as describing an efficient method for data processing. An FLIR Tau 320 sensor with an FLIR 25 mm lens attached on A Blade 350 QX2 Quadcopter was used to capture thermal infrared images with a resolution of 0.5 cm, geo-referencing them off the colour aerial imagery showing the five control points. The Pix4D was used for image processing. In comparison to other packages, the low cost and operational flexibility, along with the high spatial resolutions provided at high turnaround times, makes this platform suitable for this study as well as a number of other applications. The study also highlights that while small UAVs do not provide a universal solution, they offer a cost-effective alternative to traditional manned aerial surveying.

The use of UAVs for environmental monitoring in the geothermal sector is still in its infancy despite potential applications, low cost and operational flexibility. This is likely to change soon due to the tremendous leap forward in the availability and sophistication of UAV platforms, and advances in processing software. Technological improvements such as platform stability, simple operational procedures, advanced payloads and operating range will undoubtedly play an important part in encouraging the diverse application of UAVs.

The current interest in UAV applications is provoking a new movement of emerging users keen to apply this technology in unconventional ways. Given this, it is important that while maintaining safety, regulations also allow for the development of this new research. UAV applications suit a variety of users, applications and budgets. Hence, there is a need for users and aviation managers to work closely at this evolving stage in UAV technology to forge a safe and productive way forward.

With current and historical thermal trends and vegetation distribution noted, the next chapter examines the response of vegetation to the thermal gradients as well as other variables in the geothermal field. By embedding manipulative warming experiments within multiple sites along a natural thermal gradient, responses to temperature change and the levels of other variables is investigated. Including other variables such as soil chemistry will validate the study and enable the research to determine if warming has the greatest impact on vegetation. Geothermally heated ecosystems present an excellent opportunity to understand responses to warming across multiple spatial and temporal scales.

Chapter 5

Temperature effects on biomass and vegetation regeneration from a geothermally heated soil system

Objective 3: Evaluate the effects of soil warming on root biomass and vegetation regeneration from a geothermally heated soil system

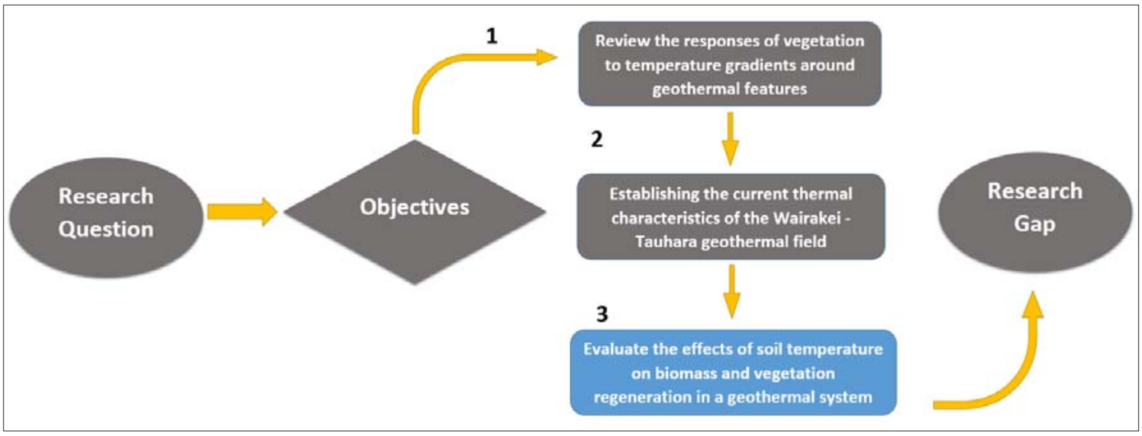


Figure 18. Objective 3.

A version of this chapter is being reviewed to be published as;

Nishar, A., M. K.-F. Bader, E O'Gorman and B. Breen, S. Leuzinger. (2016d). Temperature effects on biomass and regeneration of vegetation in geothermal areas. Frontiers in Plant Science, 7

Understanding warming effects on vegetation in its natural ecosystem is of great importance for conservation and reactive strategy planning. Predictive modelling and isolated laboratory studies have often been criticised. However, geothermal hotspots with ground heating properties can provide a substantiated indication of the level of impact warming will have on vegetation. This study investigates how warming affects vegetation regeneration and root biomass and whether there is an interactive effect of warming with other environmental variables. The research involved examining whether geothermal warming effects on vegetation regeneration and root biomass could assist with climate change predictions. Monitoring plots were arranged in a grid across the

study area to cover a range of soil temperatures. The plots were cleared of vegetation, and root-free ingrowth cores were installed to assess above and below ground regeneration rates. Temperature sensors were buried in the plots for continued soil temperature monitoring. Soil moisture, pH and soil chemistry of the plots were also recorded. Data was analysed using least absolute shrinkage and selection operator and linear regression to identify the environmental variable with the greatest influence on vegetation regeneration and root biomass. There was lower root biomass and slower vegetation regeneration in high-temperature plots. Soil temperature was positively correlated with soil moisture and negatively correlated with soil pH. Iron and sulphate were present in the soil in the highest quantities compared to other measured soil chemicals and had a strong positive relationship with soil temperature. Findings suggest that soil temperature had a major impact on root biomass and vegetation regeneration. In geothermal fields, vegetation establishment and growth can be restricted by low soil moisture, low soil pH and an imbalance in soil chemistry. Their common driver, geothermal features, explained the correlation between soil moisture, pH, chemicals and temperature. Soil temperature was negatively correlated with the distance from the geothermal features. This study demonstrated a novel approach to global warming experiments, which could be particularly useful in low heat flow geothermal systems that more realistically mimic soil warming.

5.1 Introduction

Soil temperature plays an important role in many of the abiotic and biotic processes that are integral to plant growth (Oelke & Zhang, 2004), above- and below-ground biomass (Abramoff & Finzi, 2014; Munir, Perkins, Kaing, & Strack, 2015), plant productivity (Luo, Sherry, Zhou, & Wan, 2009), nutrient uptake (Rustad et al., 2001), and diversity and distribution (Bond-Lamberty et al., 2006; Pickering & Green, 2009; Sohoulande Djebou & Singh, 2015). Changes in vegetation cover are a response resulting from both environmental and biological conditions. Several authors have reported significant relationships between temperature and vegetation indices (Wang, Cao, Chen, Rao, & Tang, 2015; Zhang, Friedl, Schaaf, & Strahler, 2004). Moreover, soil temperature influences soil moisture levels and microbial function and productivity (Lukewille & Wright 1997; Pregitzer & King, 2005).

It is generally found, based on field observations (Lapenis, Henry, Vuille, & Mower, 2014) and remotely-sensed data (Shen et al., 2014), that soil temperature levels vary widely across landscapes based on elevation (Balisky & Burton, 1995; Clinton, 2003) and climate (Kang, Kim, Oh, & Lee, 2000). However, over the last 100 years, soil temperature has risen in many areas as a result of climate change (IPCC, 2013). The average global surface temperature increased by 0.74 °C from 1906 to 2005 (IPCC, 2007) and most models predict a rise in global surface temperature of at least 1.5-2.0 °C by the end of this century (IPCC, 2013). The increase in the surface temperature during the past century has contributed to changes in vegetation phenology, species ranges, and community composition (Villarreal & Jesus, 2012; Walther, 2010) and the projected global temperature increase will generally result in an increase in near-surface soil temperatures (ACIA, 2005; Betts, 2001; Chapin & Körner, 1995; Claussen et al., 1999; Hinzman et al., 2005; Oechel, Vourlitis, Hastings, & Bochkarev, 1995), affecting soil conditions (Okkonen & Kløve, 2010; Rixen et al., 2008) and vegetation structure, composition and growth.

Warming experiments in the past have used a variety of heating methods, including electric heating (de Valpine & Harte, 2001), infrared radiation (Wan et al., 2002) , reciprocal transplants (Jonasson et al., 1993), and open- and closed-top field greenhouses (Henry & Molau, 1997). These approaches obviously have their place and contribute to our understanding, but each of these methods come with their set of limitations (Shaver et al., 2000). Geothermally-heated ecosystems have recently been identified as complementary natural warming experiments, where one can investigate long-term adaptation of real-world communities across natural temperature gradients (O'Gorman et al., 2014). Typically, geothermal hotspots have been heated above ambient conditions for a very long time (Bibby et al., 1995). The levels of soil heat, steam, and gaseous output vary amongst geothermal systems (Legittimo & Martini, 1989; McGee, 1997), depending on geological structures, the depth of the magma chamber and the water table (Legittimo & Martini, 1989). The area of soil heat emissivity depends on the geothermal heat flow (Hoang, 2010) whereas the level of impact on vegetation is a function of the distance from the geothermal heat point source (Kershaw, 1985).

Although warming affects all plant life-cycle phases, plant regeneration has been suggested to be especially sensitive (Hedhly, Hormaza, & Herrero, 2009; Walck, Hidayati, Dixon, Thompson, & Poschlod, 2011). Vegetation regeneration is a strong indicator of changes in soil conditions and an increase in soil temperature will adversely affect on vegetation regeneration levels (Althoff et al., 2016). Similarly, root biomass may change in response to altered environmental variables (Norby & Jackson, 2000). Soil temperature is a primary rate-regulating factor (Berg et al., 1993; Kirschbaum, 1995) and an increase in soil temperature may lead to an overall reduction in root biomass (Carón et al., 2015; Milchunas & Lauenroth, 2001).

This study analysed the effect of geothermal warming on vegetation by assessing plant regeneration rates and root biomass across a wide range of soil temperatures and soil chemical properties. The following questions were specifically addressed: (i) how does soil warming affect vegetation regeneration and root biomass?; and (ii) what set of variables (temperature, soil chemistry, and their interactions) best predict changes in below and above ground biomass? The hypothesis was that vegetation regeneration and root biomass would show a negative correlation with increasing soil temperature. The expectation was that soil temperature would have a far greater impact on vegetation regeneration above- and below-ground than other environmental variables.

5.2 Materials and methods

5.2.1 Study area

The Taupo Volcanic Zone (TVZ) in the North Island of New Zealand covers an area of approximately 30 × 150 km (Kissling & Weir, 2005; Soengkono, 1995), containing 23 stable and long-lived geothermal fields (Bibby et al., 1995) with varying heat outputs (Kissling & Weir, 2005). The Wairakei- Tauhara geothermal field, in particular, has distinctive assemblages of plants that survive under extreme geophysical and geochemical conditions (Boothroyd & Stark, 2000; Death & Death, 2006; Given, 1980; Healy, 1992). The section of the Wairakei-Tauhara geothermal field covered by this study is referred to as the Crown Road Geothermal Area (located at 38° 41' 28.31" S 176° 06' 54.15" E), covering an area of about 1km^2.

5.2.2 Study species

The plant species found in the study area and studied was *Kunzea tenuicaulis,* a shrub in the native tea tree genus *Kunzea* (Myrtaceae). *Kunzea tenuicaulis* propagates from seeds and is endemic to active geothermal sites, and its growth habit is a good indicator of soil temperature and geothermally altered soil (Smale, Fitzgerald, Mason, & Cave, 2009). Soil temperature has the largest influence on the distribution of *Kunzea tenuicaulis* (Given, 1980; Martin, Rodgers, & Browne, 2000) with soil acidity and chemical concentrations having minor effects (Burns, 1997; Burns B, Whaley, & Whaley, 1995; Burns & Leathwick, 1995).

5.2.3 Experimental design

To determine the effects of soil temperature on above and below-ground vegetation regeneration, an experimental trial was implemented in December 2014. A grid was delineated within the study area, consisting of eighteen 150 × 200m blocks (Figure 19). A 0.6 × 0.6m plot within each block was established to span a range of surface temperature profiles, including three ambient plots (< 19 ºC) and fifteen plots in warm to hot areas (24-50 ºC). These subsurface spot temperature measurements were taken using a depth of 15 cm to assist allocation of the plots.

All vegetation, including roots, was removed from the 0.6 × 0.6m plots, to allow regeneration rather than regrowth to take place. The 0.6 × 0.6m area had 100% vegetation coverage before the experiment was set up. The vegetation-free plots were revisited on a monthly basis until December 2015 to monitor the above-ground regeneration rate as percentage cover within a 0.5 × 0.5m area (Figure 20), allowing for a 0.1 m buffer around the perimeter of each plot (Loetsch & Haller, 1973; Sachtler, Merida, 1975). The number of new seedlings in evidence will determine the above-ground vegetation regeneration.

The ingrowth core method was used to quantify root growth (Bledsoe, Fahey, Day, & Ruess, 1999; Milchunas & Lauenroth, 2001). Ingrowth cores (Figure 21) consisted of wire cylinders (12cm long, 3.5cm diameter, 2mm mesh size), containing root-free soil from a site within the geothermal area, with similar soil temperatures. Three ingrowth cores were installed in each of the regeneration plots at the start of the experiment. A soil corer was used to create a cylindrical hole in each plot, inserting the ingrowth cores 3cm below the soil surface, and covering them with topsoil. After excavation in December 2015, the cores were transferred to the lab where the new roots were separated from the soil with sieves with 1-3 mm mesh size, rinsed and set in a water bath to be scanned. The images captured were analysed using WinRHIZO software (Regent Instruments Inc., Quebec, Canada), which separated them into five size classes by diameter: 0-0.5mm, 0.5-1mm, 1-1.5mm, 1.5-3mm and 3-4.5mm. The roots were measured using a micrometre calliper and separated using tweezers. Once scanned, the roots were separated from water, dried at 70 ºC for 65 hours and weighed to determine the biomass. 65 hours in the oven had removed all moisture from the root; any more time in the oven would have been redundant. The below-ground vegetation regeneration will be determined by the biomass of all the roots found within the plots.

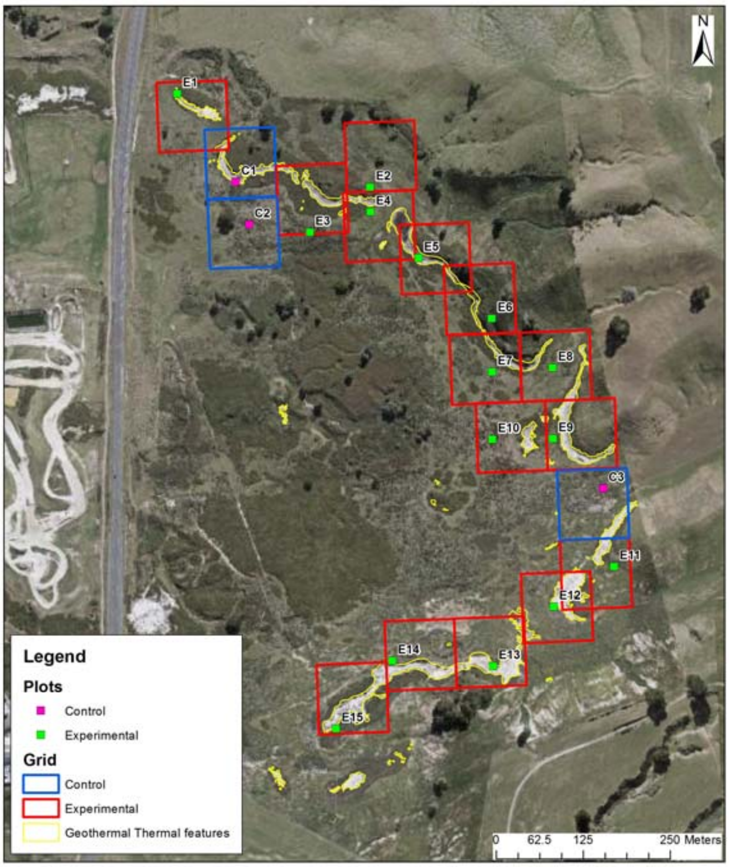


Figure 19. Layout of the grid within the study area and location of the control and high-temperature plots.

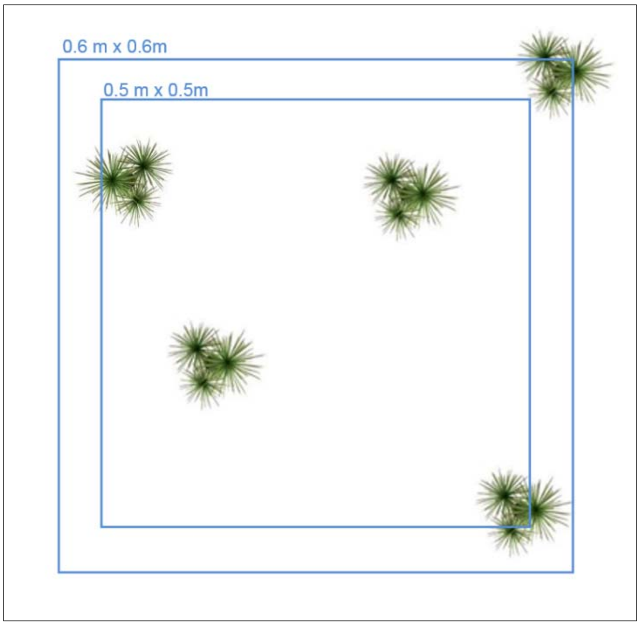


Figure 20. Layout of the regeneration plot (not to scale).

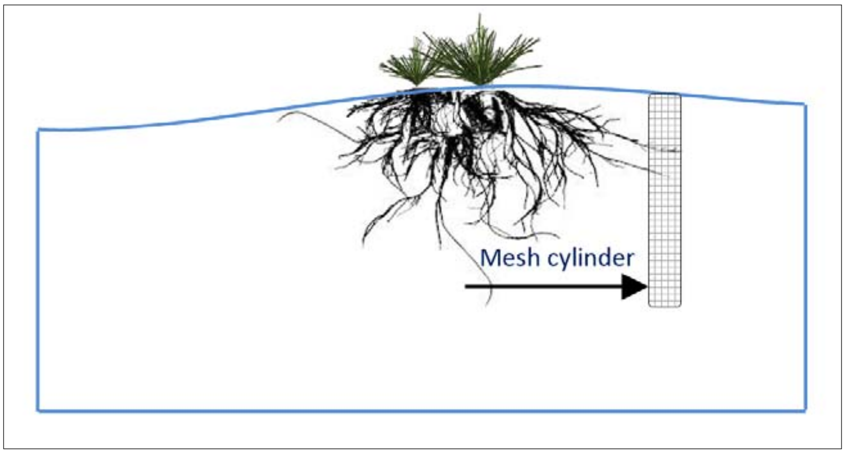


Figure 21. Set up of the ingrowth core (not to scale).

5.2.4 Environmental variables

Instantaneous subsurface spot temperature measurements were used to determine the high-temperature plot locations at the outset of the experiment. Instantaneous subsurface spot temperature was measured in all the blocks at a depth of 15cm, using a Yokogawa TX10 digital thermometer (Yokogawa Electric Corporation, Musashino, Tokyo, Japan) connected to a type K thermocouple. Once the plots were selected, continuous soil temperature measurements were used to provide a detailed temperature profile throughout the one-year duration of the experiment. For continuous soil temperature measurements, one Thermochron iButton (DS1921G) temperature logger (Maxim Integrated, San Jose, CA, USA) was buried in each of the 18 monitoring plots at a depth of 15cm and left in place from December 2014 to December 2015. The data from the iButtons was retrieved on a monthly basis.

Soil moisture readings were taken in each of the 18 monitoring plots using a Decagon Devices ProCheck meter with a 10HS soil moisture sensor (Decagon Devices, Pullman, WA, USA). Soil was taken at a depth of 15cm on a monthly basis (December 2014 – December 2016). For the soil pH analysis, a soil sample was taken from each of the plots and oven-dried. In July 2016, soil was removed using a soil corer from a depth of 15cm The oven-dried soil sample was mixed with deionised water (1:2.5 volumetric ratio of soil to deionised water) and was set for a day. After thorough mixing, each sample solution was measured using a pH meter.

Soil samples (100g) were taken 0 - 15 cm below the ground surface using a 15 × 3.5 cm (length × diameter) soil corer from each of the 18 plots. The soil samples were taken during July 2015. In the lab, the samples were oven-dried at 60 °C for three days and ground for testing. Soil samples were tested for sulphate (SO_4^{2-}), magnesium (Mg), potassium (K), iron (Fe^{2+} and Fe^{3+}), calcium (Ca), phosphorus (P), manganese (Mn), boron (B), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn) and cadmium (Cd) (Franzen, Hofman, Cihacek, & Swenson, 1999; Willett & Zarcinas, 1986).

5.2.5 Data analysis and model selection

All statistical analyses and graphics were performed using R version 3.2.2. (R Core Team, 2015). Soil temperature fluctuations from December 2014 - December 2015 were plotted to assist in assessing the effects of soil temperature on soil pH, soil moisture, soil chemicals and vegetation regeneration. Principal Component Analysis (PCA) was used to test for relationships between the predictor variables: soil temperature, soil moisture, soil pH and soil chemical levels. The relationships between variables were plotted using a biplot to aid visual interpretation. We performed a least absolute shrinkage and selection operator (package *lars*) regression to drop variables with coefficients of zero and reduce high dimensional data for the regression analysis and model selection. A simple linear regression analysis was run with each of the remaining predictor variables and either root biomass or vegetation regeneration as the response variable. Model selection was based on the Akaike's Information Criterion (AIC). The model with the lowest AIC score was selected. Since vegetation regeneration was collected as proportion data, a logit transformation (package *logit*) was applied before the regression analysis. A linear mixed effects model (package *nlme,* Pinheiro et al., 2015) was applied to assess the effects of elevated soil temperatures on root biomass.

5.3 Results

5.3.1 Soil temperature

The continuously logged soil temperature readings at the closest site to the geothermal features ranged from 18.5-70 °C and the readings at the coolest, most distant site ranged from 6.5-32 °C, from December 2014 to December 2015 (Figure 24). The soil temperature ranges of the high temperature plots were split into mid (18-43 °C) and high (> 56 °C) temperate ranges. Table 8 lists the mean soil temperature of each plot.

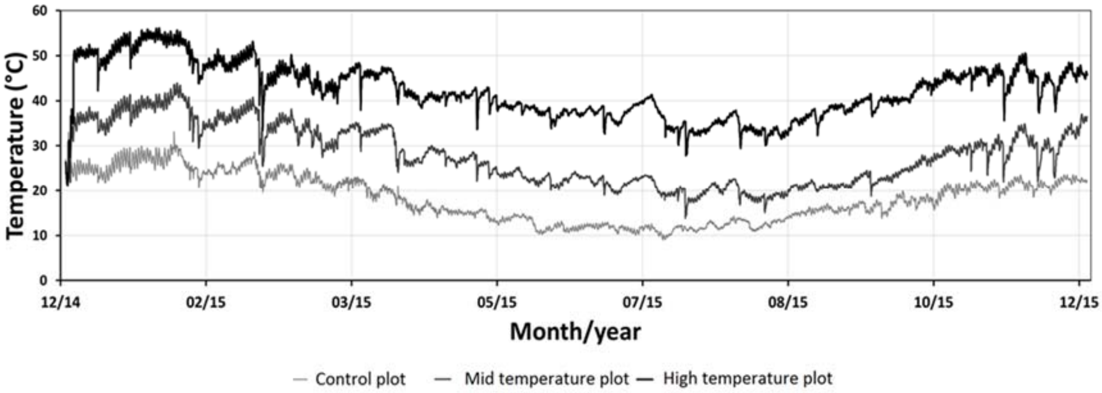


Figure 22. Hourly soil temperature fluctuations at 15 cm depth (n = 18, control: n = 3, mid temperature: n= 11, high temperature: n = 4), December 2014 - December 2015. Data captured at Crown Road geothermal area.

Table 8. Mean soil temperature of control, mid-and high-temperature plots.

Control Plots	**Mean soil temperature (°C)**
C2	16.74
C3	17.19
C1	19.11
Mid-temperature plots	
E3	19.33
E7	24.49
E4	25.65
E5	26.88
E6	27.36
E13	29.6
E9	30.56
E2	30.67
E15	36.05
E8	37.74
E11	37.93
High-temperature plots	
E10	42.05
E12	45.72
E14	45.88
E1	50.43

5.3.2 Soil moisture and pH value

Acidic soil occurs where the soil temperatures is the highest, the soil pH increases in a linear fashion with a decline in soil temperature (Figure 23 [a] t value = 9.08, $P < 0.001$, $R^2 = 0.75$). There was a significant increase in soil moisture with increasing soil temperature (Figure 23 [b] t value = 5.22, $P = 0.006$, $R^2 = 0.35$).

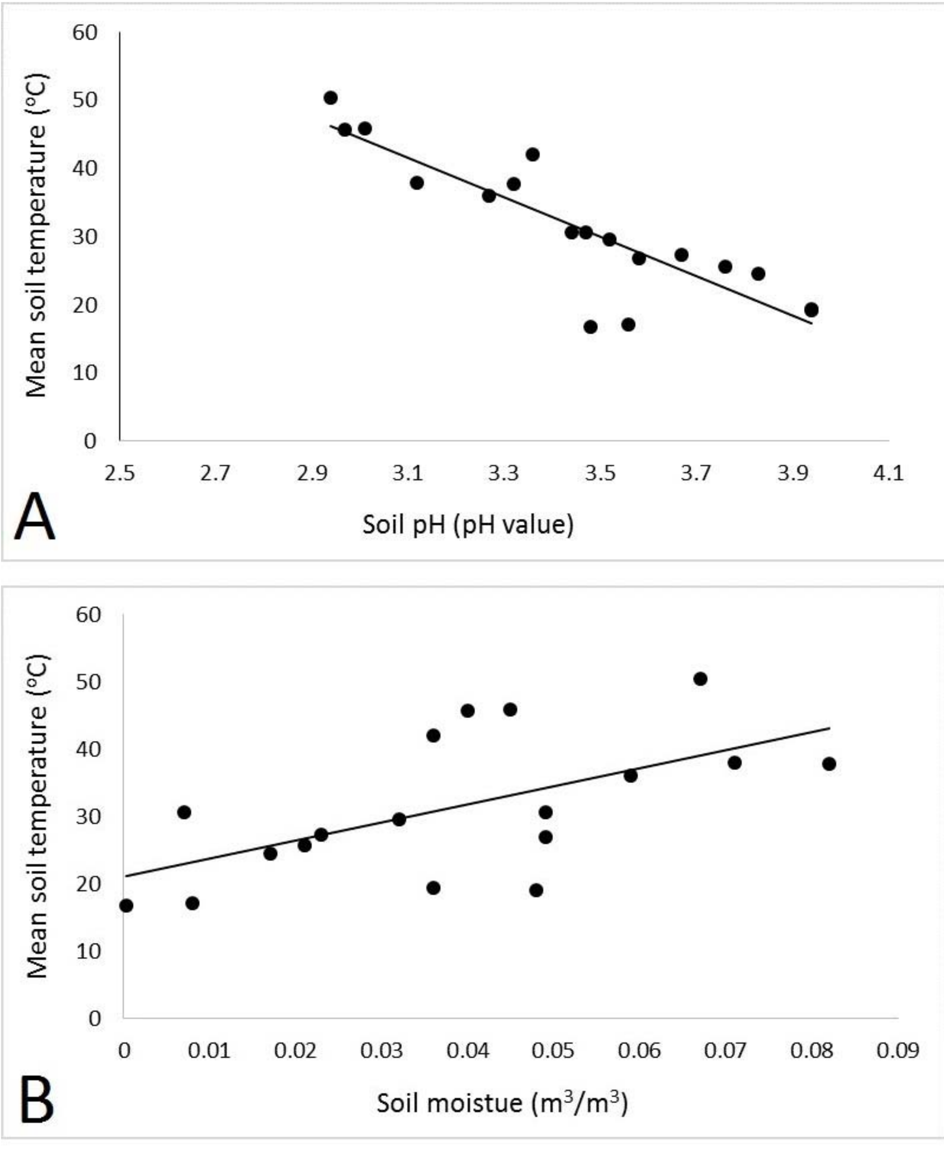


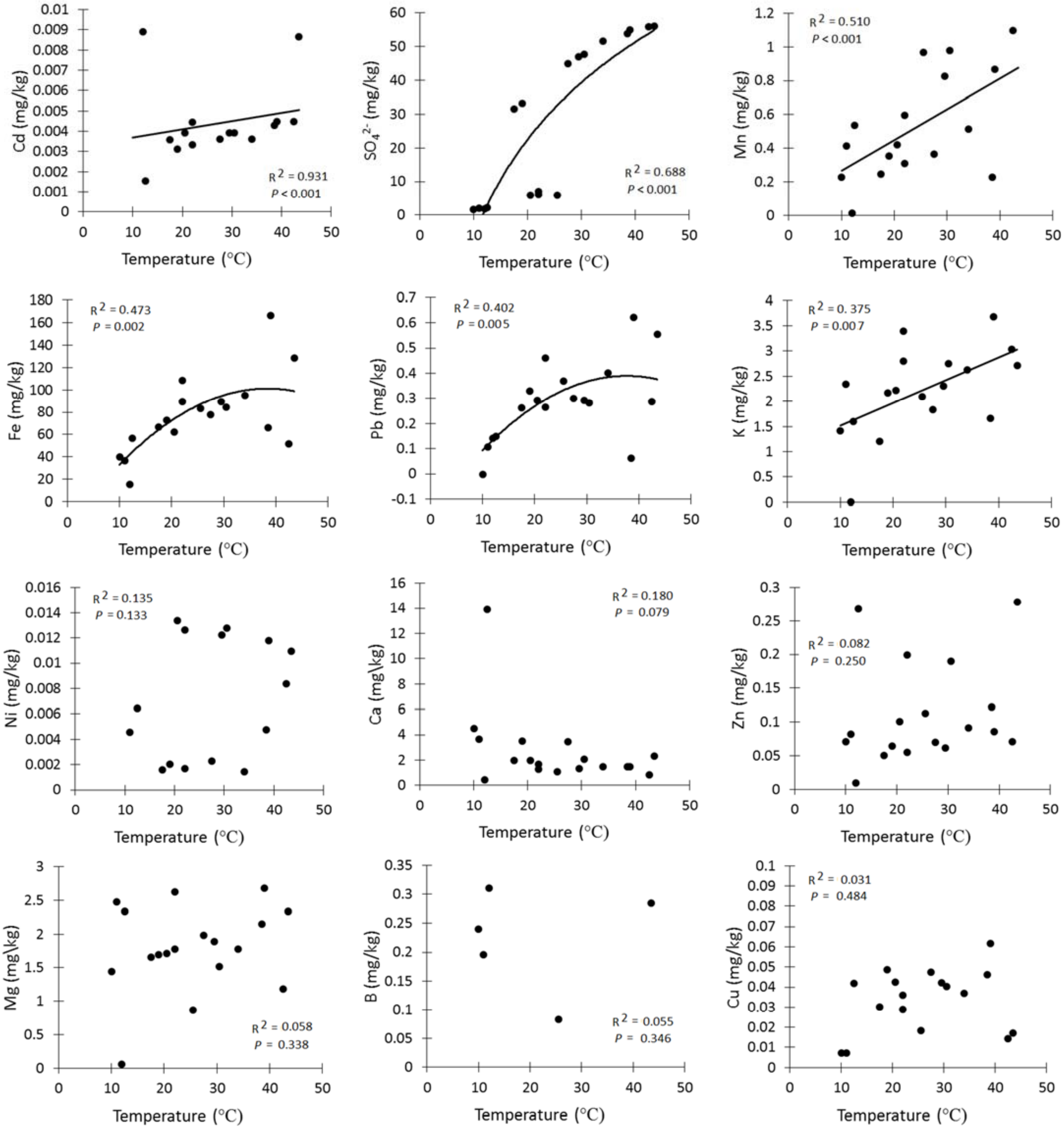
Figure 23.Mean soil temperature at 15 cm depth as a function of (a) soil pH ($y = -28.81x + 130.84$), and (b) volumetric soil moisture ($y = 268.5x + 21$), n = 18. Data captured at 15 cm depth (n = 18, control: n = 3, mid temperature: n= 8, high temperature: n = 7), December 2014 - December 2015. Data captured at Crown Road geothermal area.

5.3.3 Soil chemistry

Amongst the major elements, iron (77.3 ± 0.05, mean ± standard error) and sulphate (28.3 ± 0.06) had the highest concentrations in the soil samples (Table 9). The most rare trace element occurring at the lowest concentrations was manganese (0.6 ± 3.8). In addition, lead (0.3 ± 12.5) and nickel (0.007 ± 538) had the highest concentrations of the microelements. The linear regression (Figure 24) indicated a strong positive relationship between soil temperature and Cd, SO_4^{2-}, Mn, Fe, Pb, and K. However, there was no significant relationship detectable (Figure 24) between soil temperature and Ni, Ca, Zn, Mg, B, Cu, and P. The biplot (Figure 25) collectively displays the correlation of all the tested soil elements with soil temperature, moisture and pH; suggesting that soil temperature, soil moisture, SO_4^{2-}, Mn, Pb, K and Fe are closely related while soil pH shows a negative correlation with temperature.

Table 9. Mean and statistical values of major and minor soil elements from across the 18 plots.

Element (mg kg-1)	**Mean**	**Standard Error**	***t* value**	***p***
Ca	2.687	0.78	-1.88	0.086
Fe	77.29	0.05	3.79	0.005
K	2.216	2.37	3.1	0.013
Mg	1.787	3.88	0.99	0.367
Mn	0.615	3.79	4.08	0.003
P	5.306	0.68	-0.07	0.813
B	0.062	22.63	-0.97	0.342
SO_4^{2-}	28.28	0.06	5.94	<0.001
Cd	0.005	1186.53	0.09	0.976
Cu	0.041	70.94	-0.72	0.468
Ni	0.007	538.39	1.58	0.403
Pb	0.288	12.45	3.28	0.011
Zn	0.11	33.26	1.19	0.365



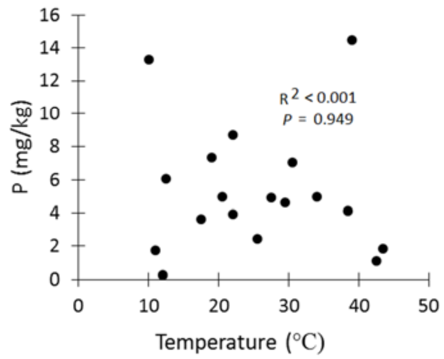


Figure 24. Soil element levels along a temperature gradient.

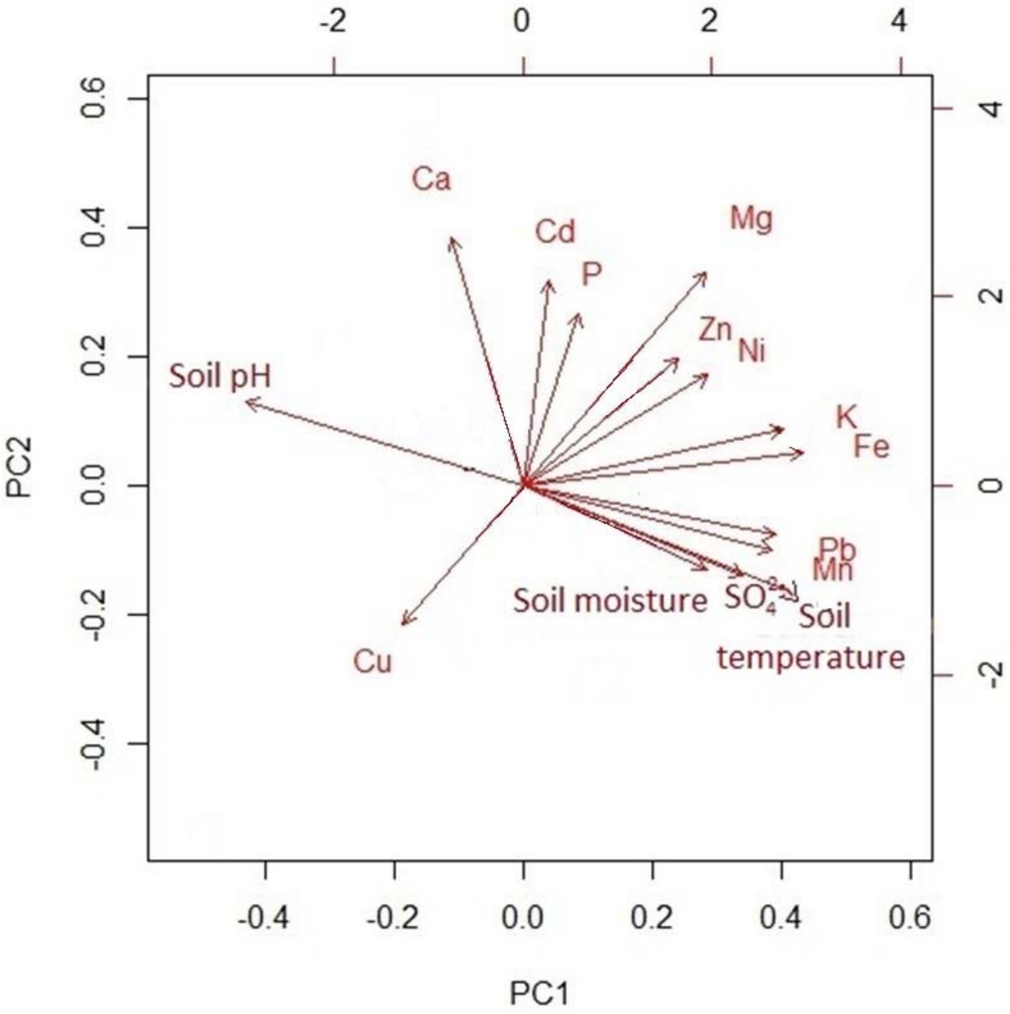


Figure 25. Principal component analysis biplot of environmental variables for 18 plots.

5.3.4 Vegetation regeneration

After applying the least absolute shrinkage and selection operator (LASSO) regression with vegetation regeneration as the response variable, the coefficients of all but two explanatory variables were zero. Amongst these two candidates, the model containing soil temperature as sole predictor variable had the lowest AIC. The regeneration coverage at the time of assessment ranged from 0-90 % in individual plots. On average, the highest regeneration of around 55% was observed at the coolest soil temperature (c. 17 °C) and declined in a curvilinear fashion with increasing soil temperature (y = -1.45x

+ 71.5, *P = 0.012*, R^2 = 0.34, Fig. 26). The control plots with mean temperatures ranging from 16.7 -19.2 °C had vegetation coverage between 50 - 90%. The intermediate plots with mean temperatures ranging from 20 - 38 °C had vegetation coverage between 12 – 35% and the high temperature plots with mean temperature ranging from 42 - 50.4 ° C had vegetation coverage between 0 – 10%.

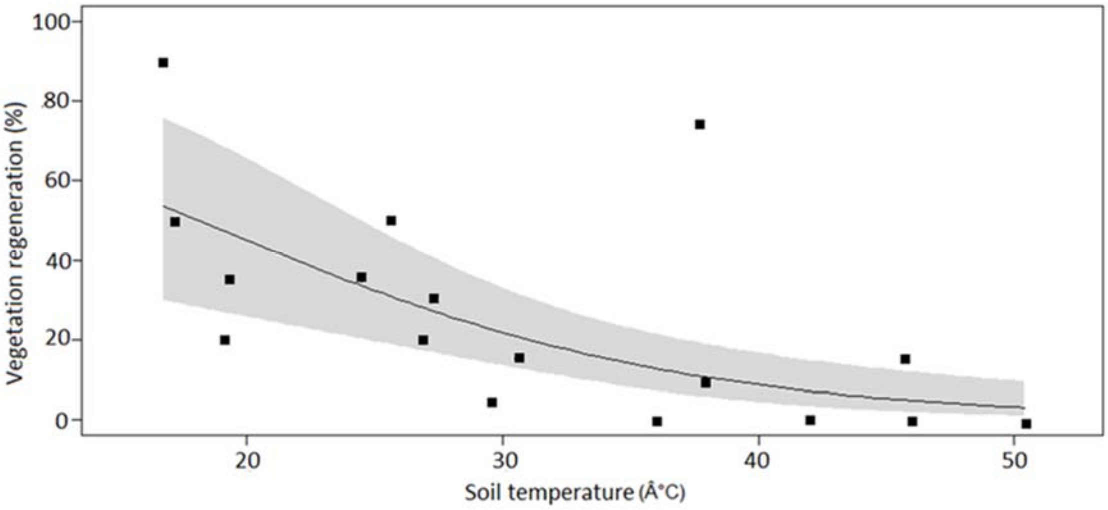


Figure 26. Percentage vegetation regeneration cover across 18 plots spanning a soil temperature gradient at the Wairakei-Tauhara geothermal field. The solid line indicates the fit of a linear regression model with a logit-transformed response variable (y = -1.45x + 71.5, P = 0.012, R^2 = 0.34,). The grey-shaded area represents the 95% confidence interval

5.3.5 Root biomass

After applying the least absolute shrinkage and selection operator regression with root biomass as the response variable, the coefficients of all but two explanatory variables were zero. Amongst these two candidates, the model containing soil temperature as sole predictor variable again had the lowest AIC. The variation in total biomass was strongly negatively related to soil temperature (Figure 27). Overall, more roots regardless of root diameter in the cores excavated 70% from the cooler control plots than plots with higher mean temperature. The difference in biomass between control and high temperature plots was greatest (243%) for fine roots (< 1.5 mm) and decreased with increasing root diameter (Figure 28).

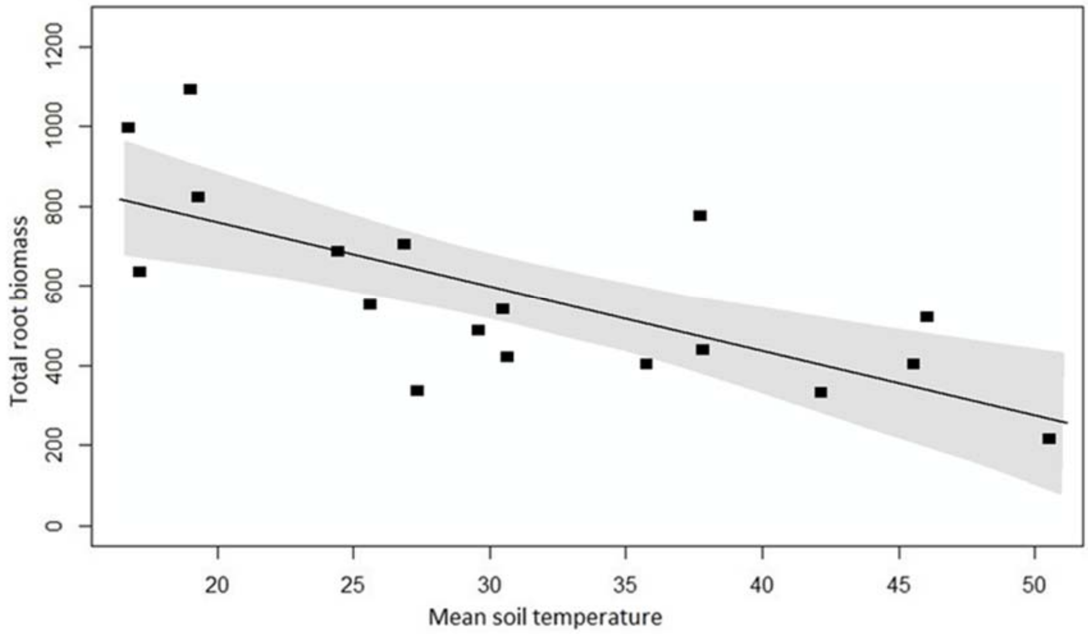


Figure 27. Root biomass at 18 plots across the temperature gradient, with linear regression ($y = -15.9x + 1067.3$, $P < 0.001$, $R^2 = 0.52$). The area between the grey-shaded area dashed lines represents the 95% confidence interval.

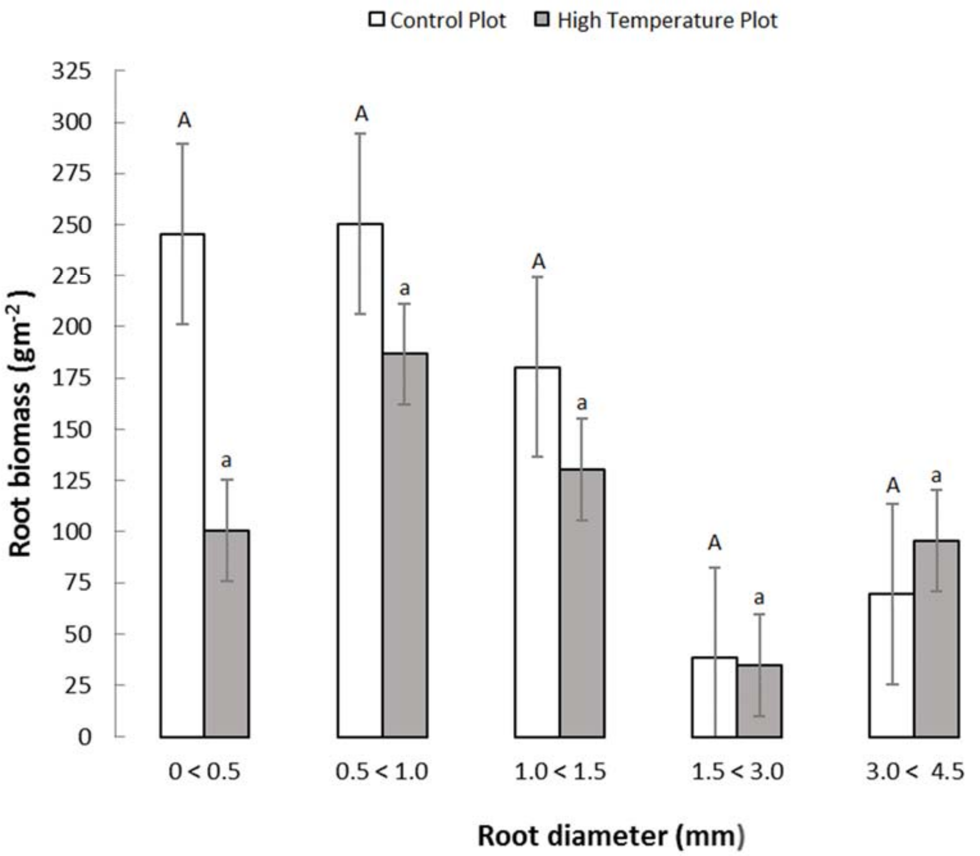


Figure 28. Root biomass of vegetation growing in control (16.67 - 30.67 ° C) and geothermally heated (19.11 - 50.43 ° C) plots. Installed December 2014, harvested December 2015, n = 15 for high temperature plots and n = 3 for control plots.

5.4 Discussion

Knowing the impact that soil warming could have on vegetation can help shape the conservation approaches of the future. This study, using geothermal heating, demonstrated the adverse effects of substantial soil warming on vegetation regeneration and root biomass. Our results indicate that after one year, two-thirds of geothermally heated plots had vegetation regeneration of less than 35%, while all control (ambient) plots showed a minimum of 50% regeneration. Similarly, the control plots had significantly more biomass in roots of < 0.5-3mm in diameter.

Our analyses showed that soil temperature is the dominating effect on vegetation regeneration and root growth. Previous studies have also suggested that in geothermal fields, vegetation establishment and growth is strongly controlled by thermal gradients

(Chiarucci et al., 2008; Elmarsdottir et al., 2003); having fundamental effects on the abiotic and biotic processes determining the distribution and density of geothermal vegetation (Aalto et al., 2013; Chapin, 1983; Olefeldt et al., 2013; Saito et al., 2009). Apart from growth rates and community composition, soil temperature may also affect species-specific growth forms, as is the case with the dominant woody species in our study system (Beadel et al., 2012; Boothroyd, 2009).

In this study, we have presented evidence that slow regeneration of above- and below-ground biomass is primarily due to a negative correlation with soil temperature. The observed regeneration rates in our high temperature plots suggest that vegetation regeneration will be slow in the case of soil warming but will not halt. Most importantly, we showed a consistent increase in root and vegetation growth in control plots and much slower regeneration in the high temperature plots. Our findings fully support our hypothesis that warming negatively affects root productivity and total biomass. For the different high temperature plots, the mean root biomass and percentage of vegetation regeneration are comparable, and both negatively correlated to soil temperature. The correlations of soil temperature with soil moisture, pH, and soil chemistry strongly suggest that soil warming will not only have a direct impact on vegetation by hindering development but also indirectly by changing soil properties (Liu et al., 2015).

There was a positive relationship between soil temperature and soil moisture, which has also be shown in previous studies (Idso, Schmugge, Jackson, & Reginato, 1975; Pratt & Ellyett, 1979; Schmer & Werner, 1974). This suggests that soil moisture content is geologically influenced in the same way as soil temperature (Legates et al., 2011; Wang, Fu, Gao, Liu, & Zhou, 2013). On the contrary, there was a negative relationship between soil temperature and soil pH. The lower pH together with high soil temperature is an indication of geothermal fluid and fume discharges (Sudarman & Suroto, 2000) containing a range of trace elements (Rodríguez, 2014). Such low soil pH levels seen in the study area could negatively influence plant growth and biomass (Al-Traboulsi, Sjögersten, Colls, Steven, & Black, 2013; Lakkaraju et al., 2010).

The content of the geothermal fluid is absorbed by the organic matter and clay minerals in the soil, which are responsible for elevated concentrations of a variety of elements (Nicholson, 2012). The elements present in the soil as well as their concentration depends on the geothermal system (Murray, 1997; Van Kooten, 1987). Different geothermal systems have varying levels of crustal heat flow that are related to the presence of hot rocks located deeper in the crust (DiPippo, 2005; Rybach, 1981) and with the transfer of geothermal heat to the surface by the convection of ground water (Helgeson, 1968; Reiter et al., 1978; Renner et al., 1975), different concentrations of elements are transported to the surface (Mahon, 1970). Our soil chemistry analyses identified Fe and SO_4^{2-} as the most abundant elements (mg/kg) amongst those tested. In a study of the Te Kopia Steamfield, New Zealand, Burns (1997) also noted high levels of extractable SO_4^{2-} and Fe. Although Fe is one of the most abundant metals in the earth's crust, its availability to plant roots is very low and it is largely driven by soil pH. At lower pH, Fe becomes more available for uptake by roots (Morrissey & Guerinot, 2009). Fe is essential for the plant’s metabolic processes but in excess amounts, it can be toxic (Aznar, Chen, Thomine, & Dellagi, 2015). Elevated amounts of SO_4^{2-} in soil can have inhibitory effects on the growth, photosynthesis and survival of plants (Austin & Wieder, 1987; Ferguson & Lee, 1983). Elements in geothermal soil are temperature dependent (Fournier, 1977). Similar to SO_4^{2-}, presence of trace elements may also be indicative of high temperature geothermal systems (Brondi, Dall'Aglio, & Vitrani, 1973; Mahon, 1970). Levels of Ca, Fe, K, Mg, Mn, P, B, Cd, Cu, Ni, Pb and Zn found in this study environment are within the range reported for other geothermal systems (Ellis, 1970; Mahon, 1970).

5.5 Conclusion

This study indicates that soil temperature is the main factor responsible for a decline in root biomass and vegetation regeneration rate. The expectation of greater occurrences of temperature extremes due to phenomena such as global warming will continue to have increasingly negative impacts on plant production and development. Therefore, understanding the response of vegetation to elevated soil temperature could help to identify the traits and tolerance mechanisms for high temperatures. This study provides an important baseline for warming experiments at geothermal sites to track effects of changing temperate conditions on the vegetation community. This information is essential to comprehend and forecast changes in the structure and composition of plant communities and develop adaptive management plans. In future studies aimed at using geothermal warming to understand the effect of changing climatic conditions, areas with very moderate warming (2-5 °C) might be most suitable.

Chapter 6

Discussion and conclusion

In this thesis, I aimed to investigate the impact of soil warming on vegetation by utilising the temperature gradient around geothermal features. To achieve this aim, I had three research objectives:

Objective 1: Review the responses of vegetation to temperature gradients around geothermal features.

Objective 2: Establish the current thermal characteristics of the Wairakei - Tauhara geothermal field

Objective 3: Evaluate the effects of soil temperature on biomass and vegetation regeneration in a geothermal system.

In this chapter, I review the main findings of my thesis, evaluate the objective, and highlight key challenges in meeting the overall research aim.

6.1 Discussion and conclusion

Research Question: Using a natural geothermal environment, how can we understand the effects of warming on vegetation?

The increased concentration of greenhouse gases is expected to alter the biotic and abiotic conditions of the atmosphere, causing increases in temperature, changes in the soil microbial activity and water content (Moss et al., 2010). Such atmospheric changes will affect nearly every aspect of human well-being, from agricultural productivity and energy use to environmental management. The tremendous importance of vegetation for agricultural and natural ecosystems underscores the necessity of understanding how a change in global temperature could affect them. Global models have been developed to simulate and predict future temperature change. While these demonstrate significant value at the continental and global scale and incorporate a large proportion of the complexity of the global system, they are inherently unable to represent local environmental dynamics (Guilyardi et al., 2009; Roeckner et al., 2003; Yongqiang, Xuehong, & Yufu, 2004). Global models are often based on laboratory studies that produce predications that may not necessarily reflect natural ecosystems.

This thesis addresses a critical gap in warming studies by conducting a warming experiment in a geothermal environment. I believe this trial will provide explicit guidance and advocate for the use of natural geothermal environments for understanding the impact of soil warming on vegetation and increasing the validity of warming experiments and predictive models.

Land surface temperature interpolated from thermal infrared imagery is a key variable explaining the impacts induced on vegetation. The relationship between land cover patterns and thermal characteristic has long been studied, but previous studies (Burns , Whaley , & Whaley 1995; van Manen & Reeves, 2012) have not considered the temporal thermal infrared data and aerial imagery as a means of comparison. Land cover changes over time, responding to thermal characteristics. Thus, a temporal analysis of vegetation is required. The identification and characterisation of vegetation distribution year after year could be done by ecological ground surveys but is only possible if the area is less than $100m^2$. Aerial time series data allowed the study of an extensive area and easily identified areas of changes. In Chapter 3, this study identified that vegetation distribution showed a dependency on land surface temperature and responded to its changes across a period. Specifically, extracting data from temporal aerial imagery demonstrated the effects of geothermal features on vegetation and validated the proposition that geothermal heat gradients present in the study area could be used for soil warming experiments. A lack of initiative for regular aerial monitoring was also highlighted in this study. Satellite and manned aerial missions are effective way to monitor and capture vegetation species distribution, spectral reflectance and vegetation biomass. However, both are limited by spatial and temporal resolutions and the high costs involved in data acquisition. These limitations can easily be overcome by the use of UAVs, which can carry various types of payloads or cameras designed for specific purposes. In this study, I captured thermal infrared and colour imagery. UAVs provide the flexibility to choose data acquisition periods and data types. UAVs also facilitate the adjustments in flying heights to obtain very high spatial resolution while maintaining 90^o viewing angles and forward and side overlap dimensions. The cost of these data acquisition methods is substantially lower than satellite and manned aerial imagery. The main advantage of the UAV is its size and reduced demand for labour that allows repeated data capture.

The study in Chapter 4 is the first known study in New Zealand to capture thermal infrared imagery of geothermal features by a UAV equipped with a thermal camera. The results of this study are important because they show that UAVs provide a viable alternative to manned aircraft, at least at the scale of this survey. They are particularly suited to the collection of high-resolution imagery, where a low altitude and slow airspeed are necessary. My study demonstrates that there are no technical barriers to the use of UAVs to produce accurate and visible thermal maps of geothermal areas. I conclude that UAV deployment has a significant potential in vegetation and geothermal monitoring and it may revolutionise methods currently used.

Understanding and predicting how soil warming affects the structure and functioning of natural ecosystems is a key challenge. Isolated laboratory and field experiments testing global change hypotheses have been criticised for being too small-scale and overly simplistic, whereas surveys are inferential and often confound temperature with other drivers. This research utilised natural thermal gradients to explore a more promising approach. Geothermal gradients were used to illustrate the biological effects of temperature in a range of environments (Burns, 1997; Convey & Smith, 2006; Norris et al., 2002). Often, the focus has been on understanding life in extreme environments rather than temperature. By isolating temperature from other drivers, its ecological effects were quantified and equilibrium responses measured in the same system across scales that were not feasible using other empirical methods. Embedding manipulative experiments within geothermal gradients demonstrated the extent to which small-scale experiments could predict the future behaviour of real ecosystems.

To illustrate this, in Chapter 5 I investigated the response of vegetation to gradients of temperature within a geothermal system. The careful integration of experimental techniques within geothermal areas helped to tease apart responses to warming across a wide spectrum of variables that show a consistent temperature dependency. This study provided a platform for investigating responses to warming at smaller scales, allowing researchers to understand better and mitigate the impact on vegetation caused by rapid warming.

In this thesis, I demonstrated new methods for data capture using a UAV and new protocols for understanding the system by combining remote sensing, GIS and time series. I also demonstrated the use of geothermal features to explain the impact of soil warming on vegetation. The geothermal features act as natural laboratories and sentinel systems to provide the key to understanding and predicting how warming can affect an active ecosystem as well as assist in protecting against the future effects of climate change. The global distribution of geothermal systems makes it possible to conduct such trials in different areas and ecosystems, providing an important understanding of climate change impacts across all environmental settings.

6.2 Limitations

In this study, aerial captured data was heavily used during analysis. Lack of thermal infrared imagery from different periods was a major limitation. The vegetation distribution pattern could only be correlated with short interval thermal infrared data. Although a sustainable level of investigation was achieved, long-term thermal, infrared data would have provided more confidences during interpolation. In New Zealand, there is no formal central depository for historical aerial data, which made searching for aerial and thermal infrared imagery challenging. In addition, the government does not see any value in scanning all film-based aerial data; currently, these operations have to be funded privately.

The study in Chapter 4 makes a noteworthy contribution to UAV remote sensing use. Nevertheless, the results were subject to certain limitations. The camera used in the study did not provide temperature calibration, thus the soil temperature and geothermal heat flow could not be calculated. Neither could the camera capture geo-referenced images. Although this study worked around these limitations, temperature calibration and geo-referenced of imagery would have provided more accurate and reproducible surface heat flow surveys of geothermal features.

The study in Chapter 5 focused on a case study with an area of 1km^2, although a bigger area of reserve was not available it would be good to spread the plots with more distance in between. This might have allowed the use of plots with more difference in soil warming. A bigger area would have also allowed for more plots without duplicating the results. The Wairakei-Tauhara geothermal field has a high heat output and the soil temperature gradient was very steep. Undertaking the fieldwork in geothermal field that has a smoother or more gradual temperature gradient would have given an opportunity to choose plots in different temperature ranges, from ambient to areas with 2-5 ºC difference. Temperature being the main variable tested, regeneration and root biomass outcomes from a range of heated plots would have given a more defined result.

6.3 Future research

This study reconfirmed the importance of both colour and thermal infrared. There is no national programme for systemic aerial data capture (colour and thermal infrared data capture). It will also be helpful for the industry to come up with a guideline of aerial data capture. Specific guidelines on resolution will enable a wide range of application by different industries.

This study demonstrated that geothermal areas can be surveyed with ease using a UAV producing accurate thermal and colour imagery. To advance the study, regular thermal imagery of the Crown Road geothermal features can now be captured to monitor the change in heat signatures. Since this study, AUT has invested in advanced UAVs that allow programmed navigation. The institution also plans to purchase a camera with temperature calibration and geo-referencing capability.

The global distribution of geothermal sites makes such field-based experiments feasible, provided there be enough vision and international collaboration. Establishing ecological observatories in geothermal systems around the world, across all ecological levels will provide a holistic understanding of the impacts of climate change on vegetation. Global sharing of the outcomes will also encourage further collaboration and support. The different geothermal sites around the world have different heat signatures and outputs. Establishing research in different sites will allow us to understand and monitor the impact of exclusive temperature and warming ranges. Although predictions have been made as to what level of temperature increases to expect, understanding the impact of warming of different temperature ranges will allow for well- thought-out precautionary approaches.

In addition, it is important to note that geothermal systems heat the soil but have no or limited impact on air temperature hence these effects may be different from the gradual changes to Earth's climate from anthropogenic effects. Therefore, it is important to repeat manipulative experiments in geothermal systems over many seasons, years and possibly decades to be able to extrapolate the results to climate change.

In this study, the regeneration plots and soil core cylinders were left in the fields for one year. Although, the trial was a success, it will be worthwhile to multiple multiply the number of plots and core cylinders in the field and retrieve the data intervals. This will allow us to see the trends in vegetation regeneration at intervals of six months over 2-4 years. Long-term vegetation data with soil temperature figures will either confirm the findings of the study or highlight other trends not yet seen.

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