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Geothermal ecosystems and the biodiversity monitoring framework: a review with recommendations

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Table of Contents

Tables

Abstract

Standardised monitoring protocols for measuring ecosystem integrity across New Zealand's diverse environments are under active development. However, no recommendations have been made for ecosystems considered dangerous to sample due to their intrinsic hazards, including geothermal ecosystems that contain heated and unstable ground. Waikato Regional Council, therefore, commissioned this review of geothermal ecosystem monitoring, including consideration of options for implementing quantitative monitoring methods compatible with the national monitoring framework. Fifty-one publications including primary peer-reviewed research, technical reviews, and monitoring reports published between 1978 and 2021 were reviewed for historical context. Monitoring of geothermal ecosystems has occurred since the 1970s. Methods and data collected vary among studies and the most widely used method may not be fit for all purposes to which it is put. Monitoring geothermal vegetation presents a range of challenges: difficulty of access, high habitat diversity within sites, and habitats and species susceptible to trampling impacts. These challenges were discussed during a workshop on potential monitoring methods. Three recommendations with regard to monitoring geothermal ecosystems are made. First, methods to quantitatively measure geothermal ecosystem integrity should be added to the suite of indicators currently being monitored. Second, quantitative assessment of the integrity of geothermal habitats should be achieved by applying the methods for wetland ecosystems proposed by Bellingham *et al.* (2021) for geothermal wetlands; and a modification of methods proposed by Bellingham *et al.* (2021) for other geothermal habitats that are not dangerous. Third, a new approach to measuring vegetation structure and cover abundance using drones and 1 m^2 plots could be explored to extend measurement of ecosystem integrity into dangerous areas.

Executive summary

Measuring the integrity of Aotearoa New Zealand's ecosystems is important to ensure that we look after them properly. One way of measuring an ecosystem's integrity is by comparing it with similar ecosystems from around New Zealand, to see whether it is in better or worse condition. Objective measurement of ecosystem integrity avoids subjective and observer bias and is replicable and independently verifiable. These properties allow scientific measurement of ecosystem integrity to be made by anyone, anywhere, and at any time, so long as standardised methods of collecting data are followed.

A proposal for standardised methods for measuring ecosystem integrity was made by Bellingham *et al.* (2021), based on two core principles that have been widely used in scientific studies in New Zealand and abroad. The first principle is that observations should be fixed in extent and location, because repeated observations from precisely the same place allows changes over time to be detected. The second principle is that observations from different places should be made in precisely the same way, because this allows differences among sites to be detected.

No one method can be usefully applied to all the terrestrial ecosystems in New Zealand, though consistent methods have been developed for use across shrubland, grassland, and wetland ecosystems (e.g., Wildland Consultants 2018b). Bellingham *et al.* (2021) therefore devised a set of six methods, each tailored to a different broad ecosystem type but based on the same principles and collecting the same kinds of data, all of which flows into a national monitoring framework. Unfortunately, no recommendations were made in Bellingham *et al.* (2021) as to how ecosystems deemed dangerous to sample should be measured, including geothermal ecosystems. Geothermal ecosystems are challenging. They are dangerous, at least in part, due to the presence of geothermal heat and unstable soils. They are also diverse due to the wide variation in soil temperatures within a site, the kind of geothermal activity that occurs, the dynamic nature of geothermal activity, and the landscape settings in which they occur.

For historical context we reviewed 51 publications including primary peer-reviewed literature and technical reports. A variety of methods have been used to monitor and study geothermal ecosystems. While some methods and indicators are standardised and applied widely across geothermal sites, these do not fulfil all the requirements set out by Bellingham et al. (2021). Therefore, including geothermal ecosystems within the national monitoring framework means that additional monitoring methods must be applied to them. Monitoring must simultaneously meet the exacting requirements of repeated measures and accommodate the challenges associated with geothermal ecosystems.

A workshop representing regional councils, iwi, the electricity industry, universities, the Department of Conservation and the private sector discussed options to meet these dual requirements. Recommendations from this workshop were taken in consideration along with a broad review of literature on monitoring methods, particularly with regards the use of emerging technologies using unmanned aerial vehicles, which were regarded by participants as a key tool for accessing and measuring these dangerous sites. For those parts of the national monitoring framework where dangerous sites can be avoided without introducing bias, we recommend the methods provided by Bellingham *et al.* (2021) be adopted, directly for geothermal wetlands, and indigenous and exotic fauna, or with modification for other geothermal vegetation. Modified methods are based on a different range of plot sizes, and the methods appropriate to the vegetation stature in each, following Bellingham *et al.* (2021) but in all instances recording percentage cover values, rather than their ordinal cover scores.

Drones can be used to extend sampling into dangerous areas. Many dangerous areas are hot, so are covered by sparse, short-stature vegetation, which can be measured using 1 m^2 plots located onto high-resolution, orthorectified images.

The workshop also considered different strategies for locating plots in geothermal ecosystems to obtain representative samples of the vegetation types that occur.

For terrestrial geothermal vegetation, we recommend the use of plots whose size scales with vegetation stature. The following plot sizes are recommended for terrestrial geothermal habitats:

Forest, tall (>2 m) scrub, and tall shrubland:	10 x 10 m
Short (<2 m) scrub and short shrubland:	2 x 2 m
Mossfield and lichenfield:	1 x 1 m
Raw soil field	1 x 1 m

We recommend these plots be located in a stratified random manner, with the overall site being subdivided by habitat and vegetation type. The basis for this subdivision could be a standard vegetation classification system, however, the subdivision used must include rare and uncommon vegetation and habitat types that are found in geothermal ecosystems, to ensure they are included within the sample of plots.

For dangerous sites, overflying a drone to capture high resolution imagery, with plots located onto and measured from the orthorectified images that result is recommended. The plot sizes should follow the vegetation stature, as recommended for plot sizes above. Data on species diversity and cover abundance should be obtained from images. A comparison of data capture from aerial images and ground-based measurement should be undertaken for a selection of plots measured using both methods, to establish expected error rates.

1 Introduction

Wildland Consultants were commissioned by Waikato Regional Council (WRC) to augment a report prepared by Landcare Research on ‘Standardised methods to report changes in the ecological integrity of sites managed by regional councils' (Envirolink Grant: 2039-HBRC252; Bellingham *et al.* 2021). Geothermal habitats were among those deemed ‘ecosystems dangerous to sample’, and while the report provided some guidance about what might be useful indicators of ecological integrity, no recommendations on monitoring methods in dangerous ecosystems were made. Instead, the report urged further work to ‘develop appropriate means to quantify changes in ecological integrity of sites that are dangerous to sample’ (Bellingham *et al.* 2021: 32). WRC is responsible for the largest area of geothermal habitat of any of the sixteen regional and unitary councils within Aotearoa/New Zealand and wishes to provide more input into the development of standardised monitoring for geothermal ecosystems.

Opportunity

Manaaki Whenua - Landcare Research (MWLR) are continuing to develop standard monitoring methods for different ecosystem types within the context of a biodiversity monitoring framework, and an opportunity exists to provide a ‘module’ for geothermal habitat. Given that the Waikato has more geothermal habitat in Aotearoa-New Zealand than any other Region, it is fitting that WRC has input into the development of standard monitoring methods.

This project is the first stage in providing this input and involved:

- Collating background information on geothermal sites that have had past flora and fauna (indigenous and exotic) monitoring, different monitoring methods used, monitoring outcomes reported, and the most up-to-date mapping (e.g., geothermal sites within the Wairākei-Tauhara, Mokai, Rotokawa and Ngatamariki geothermal systems). Sites that are monitored as part of resource consents were also included.
- Discussion at a workshop of key stakeholders.
- Providing key findings and recommendations.

2 Methods

2.1 Background data collation

We assessed monitoring methods for geothermal ecosystems described in 51 reports and publications produced between 1978 and 2021 for a range of purposes including consent monitoring, environmental reporting, and scientific research (Appendix 1). These were selected based on their being cited in reference lists of primary peer reviewed publications, and in technical reports held at the Rotorua office of Wildland Consultants. The list is not exhaustive but does encompass the range of methods and purposes associated with monitoring activities. We scored each for the presence of different monitoring methods associated with mapping aerial extent of sites, describing and quantifying vegetation pattern, and surveying for threatened plant and animal species. Summary counts were generated from the scoring only. No analyses of these background data were performed.

2.2 Workshop

Following the background data collection, a workshop was held with relevant stakeholders from Iwi, Regional Councils, Industry, and the Research sector to discuss the objectives of monitoring, and how those may be achieved with respect to the Biodiversity Monitoring Framework in geothermal areas (the list of participants is provided in Appendix 3). Input from participants was incorporated into the recommendations made in this review.

3 Biodiversity monitoring framework

Aotearoa/New Zealand has a national-scale biodiversity monitoring programme in the form of the Department of Conservation's Biodiversity Monitoring and Reporting System (Tier 1). This programme covers terrestrial biodiversity across New Zealand's public lands, which comprise 32% of the land area, with monitoring occurring on an 8 × 8 km grid. This grid network does not capture geothermal sites within the Taupō Volcanic Zone (https://www.doc.govt.nz/our-work/monitoring-reporting/plot-level-report/).

Outside of the Department of Conservation estate, monitoring is the responsibility of regional and unitary authorities, but there is not yet a coordinated approach to monitoring. The methods proposed for ground-based monitoring of ecological integrity (Bellingham *et al.* 2021) addressed the current lack of a national framework for monitoring biodiversity and ecological integrity in ecosystem types outside of New Zealand's conservation estate, i.e., those areas largely falling under the responsibility of Regional Councils (with some also on LINZ and transport agency land, defence land, etc).

A key challenge which a national biodiversity monitoring framework must address is the range of ecosystem types to monitor, ideally using methods for each that are compatible with the established Tier 1 Biodiversity Monitoring Framework. The Tier 1 Framework is broad scale monitoring in a national context that began in 2011, based on plots established in 2002-2006, and in some cases, earlier. It involves regular assessment of vascular plants, birds, and pests at locations 8 kilometres apart and spaced evenly across the landscape. A national context provides reference sites from the conservation estate for measuring ecosystem integrity (Bellingham *et al.* 2021). Another benefit of a national context is that it encourages consistency in monitoring among councils. Statistical and other mathematical methods can then be used to assess the effectiveness of management actions. Bellingham *et al.* (2021) recommended permanent, square, fixed-area plots, ranging in size from 1 to 400 m^2 depending on the ecosystem, as the basis for the biodiversity monitoring framework. Essentially, combining fixed-area plots with the RECCE method maximises compatibility with the established plot-based methods employed in the Tier 1 monitoring framework.

However, the benefits of this national framework will be limited in rare ecosystems which are of restricted occurrence, including geothermal ecosystems, which are not captured within the Tier 1 Framework. Geothermal ecosystems may also be dangerous to sample, which further complicates monitoring of them. The aim of this project, including review, workshop and technical report, is to provide recommendations for monitoring geothermal ecosystems in keeping with the guiding principle of compatibility with the Biodiversity Monitoring Framework advocated by Bellingham *et al.* (2021), for the reasons stated therein.

4 Overview of geothermal ecosystems

For the purposes of this report, geothermal ecosystems are defined as all geothermal habitat that includes vegetation dominated by vascular plants, non-vascular plants, geothermally influenced bare ground (referred to in many studies as 'non-vegetated raw-soilfield' and which often contain scattered patches of non-vascular and vascular plants), and emergent wetland vegetation. It does not include open geothermal water. The definition of geothermal vegetation is consistent with the definition of Merrett and Clarkson (1999).

> *Geothermally influenced terrestrial and emergent wetland vegetation are plant communities that have compositional, structural, and/or growth rate characteristics determined by current or former inputs of geothermally-derived energy (heat) or material (solid, fluid, or gas).*

Merrett and Clarkson 1999

Compositional, structural, and/or growth rate characteristics of geothermally influenced terrestrial and emergent wetland vegetation include the unexpected presence of species usually found in warmer climates or at lower altitudes or latitudes (disjunct populations), prostrate or stunted growth forms, and with reduced growth rates. Merrett and Clarkson (1999) classified geothermal habitats into four broad categories:

- heated ground.
- geothermal wetlands.
- cooled hydrothermally altered soils.
- with atmospheric influence from nearby regular toxic gas emissions, or warm micro-climates created by nearby hot-springs discharge.

Geothermal ecosystems and vegetation are naturally rare in Aotearoa New Zealand (Williams *et al*. 2007) and internationally. Four types of geothermal ecosystems (fumaroles, geothermal stream sides, geothermally heated (dry) ground, and geothermal hydrothermally altered ground (now cool)) have been classified as Critically Endangered in Aotearoa New Zealand (Holdaway *et al*. 2012, Wiser *et al.* 2013). Geothermal wetlands with emergent vegetation were not included in the assessment of Holdaway *et al.* (2012) or in Wiser *et al.* (2013) but provide habitat for several Threatened and At-Risk plant and bird species and are greatly reduced in extent due to land use change and drainage. Due to the relative rareness of geothermal wetland extent, they could also be considered a naturally rare ecosystem.

Most high energy geothermal fields in Aotearoa New Zealand occur within the Taupō Volcanic Zone in the central North Island. Approximately 71% (777 hectares, excluding geothermal water; Wildland Consultants 2014, and various updates) of the total extent of geothermal vegetation in Aotearoa/New Zealand (excluding Kermadec Islands and offshore islands of the Bay of Plenty) occurs within the Waikato Region, with most of the remainder in the Bay of Plenty Region (around 322 hectares; Wildland Consultants 2020). Geothermal ecosystems occupy less than 0.01% of the total area of Te Ika-a-Māui/North Island. Geothermal vegetation and habitats are also present on offshore islands in the Bay of Plenty including Moutohorā/Whale Island and Whakaari/White Island.

Outside the Taupō Volcanic Zone, few other geothermal features (mostly small hot springs) are present elsewhere in Aotearoa New Zealand (in the Hauraki Gulf, in Northland at Ngawha, and scattered in the North and South Islands), although these generally have little or no associated geothermal vegetation. Geothermal systems are associated with active volcanism, and many hot springs are associated with faults and tectonic features. The geothermal vegetation on Kermadec Islands (Sykes 1965) is not considered in this assessment, but the crater system on the Kermadec Islands is likely to contain several hundred hectares of geothermal vegetation.

Ecosystem pattern is driven by many interacting factors, including disturbance history and the combination of climatic, topographic, and edaphic variables. In most terrestrial ecosystems, these typically manifest on relatively large spatial scales, with the result that climax vegetation communities change on the scale of hundreds of meters or kilometres, as latitude or elevation increase and as underlying geology changes. However, pattern in some ecosystems and habitats are driven by gradients which manifest over relatively small spatial scales. These include saline ecosystems wherein there are often pH, conductivity, and moisture gradients that influence vegetation on scales of tens to hundreds of metres (Allen *et al.* 1997). In wetland ecosystems, drainage, pH, and nutrient availability are the major determinants of vegetation pattern (Dickinson and Mark 1994; Johnson and Gerbeaux 2004). The determining environmental gradients in these ecosystems are generally stable.

Geothermal ecosystems are also characterised by vegetation patterns driven by steep environmental gradients over relatively small spatial scales, sometimes less than one metre. One important driver of vegetation pattern in geothermal ecosystems is soil temperature (Smale et al. 2018), which is itself the result of geothermal activity (Burns 1997). Because geothermal activity is dynamic, soil temperature profiles in geothermal ecosystems are subject to natural variation as geothermal activity waxes and wanes. This can occur over varying timescales ranging from days (in the case of a hydrothermal eruption) to decades (more gradual heating or cooling).

There are, then, two fundamental challenges for monitoring design associated with geothermal ecosystems.

The first is the existence of steep environmental gradients over small spatial scales, in the order of metres, which have profound effects on vegetation structure and composition (Burns 1997). The second is the inherent dynamism of the geothermal activity which drives pattern in geothermal ecosystems. Thus, the gradients are spatially and temporally dynamic; challenges which a meaningful and durable medium to long term monitoring protocol must accommodate.

Geothermal habitats have a diverse range of vegetation types and conditions, and this presents the second challenge for monitoring. The varied nature of geothermal surface manifestations produces rare and unusual habitats for plants due to varying combinations of soil temperature, soil chemistry, hydrology, and localised protection from frosts. Vegetation types present at geothermal sites include lichenfield, mossfield, herbfield, fernland, scrub, shrubland, rushland, sedgeland, reedland, forest, wetland, open water and geothermally-influenced bare ground. Many geothermal sites are dynamic and unstable, and changes in surface geothermal activity are reflected in relatively rapid changes in the extent and composition of geothermal vegetation over time. Within the Waikato Region geothermal sites occur from near sea level, e.g., Kawhia and Otua/Hot Water Beach to the subalpine zone on Mt Tongariro. The habitats are widely variable and include thermal ground, steamy habitats alongside streams, hot springs, ponds, and mudpools, forest habitats, non-vegetated habitats, wetlands with emergent vegetation (e.g., sedgeland and reedland), and mossfield and lichenfield. The vegetation pattern is often complex, and the locations of natural surface features can vary through time. Care needs to be taken in interpretation of changes revealed by monitoring at geothermal sites due to this natural variation.

Plant species present in geothermal habitats can be divided into three groups:

i. Relatively common indigenous plant species that may also occur in neighbouring non-geothermal vegetation but can tolerate conditions in geothermal habitats. Examples include mānuka (*Leptospermum scoparium*), mingimingi (*Leucopogon fasciculatus*), monoao (*Dracophyllum subulatum*), tūrutu (*Dianella nigra*) and rārahu/bracken (*Pteridium esculentum*).
ii. One plant species that is endemic and restricted to geothermal habitats in North Island, Aotearoa New Zealand. This is geothermal kānuka (*Kunzea tenuicaulis*). The growth form of geothermal kānuka is highly plastic (de Lange 2014), with height tending to decrease with increasing soil temperatures and low sprawling plants on the hottest ground (Burns 1997). Geothermal kānuka has an ectomycorrhizal association with the fungus *Pisolithus* sp. (Moyersoen and Beever 2004).

iii. Geographically isolated (disjunct) populations of subtropical and warm temperate plant species (Given 1989). Geothermal sites mimic aspects of these species' usual habitats in locations beyond their normal latitudinal and/or altitudinal ranges (Given 1995). For example, the ferns *Dicranopteris linearis* and *Nephrolepis flexuosa* occur in tropical and subtropical climates abroad but only at geothermal sites in Aotearoa New Zealand (excluding the Kermadec Islands). Other ferns and lycophytes occur in geothermal areas at altitudes that are higher than they would typically grow (e.g., *Thelypteris confluens, Cyclosorus interruptus*, *Lycopodiella cernua,* and *Psilotum nudum*). Many of the unusual species are frost-intolerant and geothermal conditions such as steam and heated soils protect them from these freezing events.

Eighteen nationally Threatened or At Risk vascular plant species (de Lange *et al*. 2018) are known to occur in geothermal sites in the Waikato Region and Bay of Plenty Regions (Table 1). The Waikato Region contains the largest populations of geothermal kānuka (Threatened – Nationally Endangered) in Aotearoa New Zealand, key populations of *Dicranopteris linearis*, *Christella* aff. *dentata* ("thermal") (both Threatened – Nationally Endangered), and key populations of five At Risk species.

Table 1 Nationally Threatened and At Risk vascular plant species[1] of geothermal habitats in the Waikato and Bay of Plenty Regions.

Scientific Name	Threat Ranking
Ferns	
Christella aff. *dentata* ("thermal")	Threatened – Nationally Endangered
Cyclosorus interruptus	At Risk – Declining
Dicranopteris linearis	Threatened – Nationally Endangered
Hypolepis dicksonioides	At Risk – Naturally Uncommon
Nephrolepis flexuosa	At Risk – Naturally Uncommon
Schizaea dichotoma	At Risk – Naturally Uncommon
Thelypteris confluens	At Risk – Naturally Uncommon
Orchids	
Caladenia alata	At Risk – Naturally Uncommon
Caladenia atradenia	At Risk – Naturally Uncommon
Caleana minor	Threatened- Nationally Critical
Calochilus paludosus	At Risk – Naturally Uncommon
Calochilus robertsonii	At Risk – Naturally Uncommon
Corunastylis pumila	At Risk – Naturally Uncommon
Sedges	
Fimbristylis velata	At Risk – Naturally Uncommon
Dicotyledons	
Korthalsella salicornioides	Threatened – Nationally Critical
Kunzea robusta	Threatened – Nationally Vulnerable
Kunzea tenuicaulis	Threatened – Nationally Endangered
Leptospermum scoparium	At Risk – Declining

Geothermal ecosystems also have a unique fauna, including thermophiles, which are obligately-dependent upon geothermal habitat. The known obligate thermophiles are all invertebrates and include the mosquito *Culex rotoruae* (Dumbleton 1968), whose larvae inhabit thermal pools, and the fly *Ephydrella thermarum* (Dumbleton 1969). Other obligate thermophiles, or unique geothermal invertebrates, may be identified as the invertebrate fauna associated with geothermal areas becomes better known. Bird and bat presence in geothermal habitats reflects habitat patterns in the wider landscape. Few targeted lizard surveys have been undertaken at geothermal sites and it is possible, that unique lizard species inhabit these areas. Freshwater species present generally reflect the aquatic conditions in geothermal sites. Fish are absent from geothermal streams where water is too hot, acidic, or otherwise unsuitable. Freshwater

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[1] As per de Lange *et al.* (2018).

macroinvertebrate populations, and macrofaunal communities are also influenced by physico-geothermal parameters (Boothroyd 2009).

5 Purpose and goal of monitoring at geothermal sites

The overarching goal of the Bellingham *et al.* (2021) proposal for a standardised monitoring framework was to facilitate a coordinated, empirical assessment of indicators of ecological integrity by regional councils around New Zealand.

Measuring ecological integrity is a key goal of the Biodiversity Assessment Framework (Lee *et al.* 2005; McGlone *et al.* 2020). What ecological integrity means and its links to Te Tiriti o Waitangi through mauri are described by McGlone *et al.* (2020). In essence, ecological integrity can be summarised in terms of ecosystem composition and function: what should be there is there, and what is there is functioning as it should. The goal of monitoring indicators of ecological integrity in geothermal ecosystems is to ensure that ecosystem character and biodiversity are maintained in different management settings (including geothermal energy extraction) and in the face of other ecological pressures (e.g., pest plants and animals). In practical terms deriving objective benchmarks for assessing ecological integrity can be challenging, especially in naturally dynamic ecosystems, but comparisons with other less modified or unmodified sites enable an indication of relative integrity to be obtained (McGlone *et al.* 2020). Comparison among sites within a region or more broadly requires a harmonised approach to monitoring, one which yields objective, repeatable, and independently verifiable data generated by unbiased sampling as the basis for consistent reporting. Systematic biodiversity monitoring is at the core of the biodiversity monitoring framework (Bellingham *et al.* 2021) and is defined by McGlone *et al.* (2020, p.4), as

‘monitoring underpinned by statistically valid selection of monitoring plots, sites or locations; establishment of strict data collection protocols; and characterised by repeat measures.’

Key questions for consideration are:

1) What are indicators of ecological integrity in geothermal ecosystems, and
2) How are those indicators best measured in line with monitoring principles?

Other questions to consider when defining the purpose and goal of monitoring at such sites include:

1) What information needs to be collected to align the programme with a national framework?
2) What information needs to be collected for Council purposes?
3) The purpose of monitoring. Is the information being collected for state of the environment reporting, to inform future management, or both?
4) How do we ensure that existing monitoring data is archived and accessible?
5) How costly should monitoring be?
6) What do we define as a ‘site’; should monitoring be undertaken at the individual geothermal manifestation level, per geothermal field, or per geothermal system?

6 Existing monitoring at geothermal sites in the Taupō Volcanic Zone

6.1 Historical overview

Monitoring (broadly defined) of geothermal ecosystems within the Waikato and Bay of Plenty Regions has been undertaken regularly to some degree for many years, and geothermal ecosystems are possibly the most comprehensively monitored of all of New Zealand's rare ecosystem types. A summary of monitoring reports assessed is included in Appendix 1.

Geothermal vegetation monitoring was initially developed as a cost-effective way of estimating the extent and heat loss of thermal ground (Dawson and Dickson 1970). However, geothermal vegetation is now recognised as being important in its own right and effects on geothermal vegetation are specifically considered in resource consent applications.

Geothermal vegetation monitoring has been more systematic since 1996 (e.g., Burns *et al.* 1996) with the marking and regular repeat measures of permanent grids or plots. Monitoring frequency among studies has varied from annually to six-yearly. Some studies have involved one-off measurements that have not been repeated. Monitoring methodology has differed among areas and the consequences of this are discussed below. In general, long-term geothermal vegetation monitoring comprises a network of permanent monitoring plots and photo points, almost all within Development Geothermal Systems. Within the Waikato Region, geothermal systems have been classified into one of four management categories by Waikato Regional Council[1]. A total of *c.*354 ha or 41% of geothermal habitat has been mapped within Development Geothermal Systems; *c.*64 ha or 7% has been mapped in Limited Development Geothermal Systems; *c.*10 ha or 1% within Research Geothermal Systems, and *c.*386 ha or 45% has been mapped in Protected Geothermal Systems (Wildland Consultants 2014).

Vegetation cover, ground temperature (at 10 cm depth) and a variety of other measurements are made at regular intervals (generally every four or five years) in these areas. Any changes are analysed in comparison to data from previous years and potential causes of changes are identified where possible. It can be difficult to isolate a cause of change because geothermal habitats are naturally dynamic and the robustness of monitoring data is limited by the frequency of monitoring and modifications to the methods over time. Long-term monitoring data from geothermal areas that are not exploited for energy may provide a valuable reference for determining changes to vegetation caused by exploitation. However, we are not aware of any consistent and comparable monitoring programmes within Protected Systems. The only similar monitoring which has been undertaken in a Protected System is a one-off study by Burns (1997) at Te Kopia, which cannot provide a reference for natural changes in geothermal vegetation.

In general, monitoring (broadly defined) of geothermal ecosystems in the Waikato and Bay of Plenty Regions has been motivated by three factors: a general curiosity regarding the biodiversity values associated with geothermal ecosystems, significance assessment for the purposes of regional policy and planning, and as a condition of consent to extract geothermal energy for electricity generation. There have been two monitoring themes tied to these consents, one being the condition of geothermal vegetation, the other the condition of populations of geothermal plant species, in particular a suite of fern species whose New Zealand occurrences are primarily associated with geothermal sites in the Taupō Volcanic Zone. As befits the disparate suite of objectives entailed by these motivating factors, a range of monitoring protocols have been applied in geothermal ecosystems.

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[1] https://www.waikatoregion.govt.nz/environment/natural-resources/geothermal/classifying-geothermal-systems/. Accessed 6 August 2018.

The assessment of significance has been based in large part on detailed mapping of vegetation types from aerial photography coupled with ground truthing to establish the composition of observed vegetation types. This approach to mapping vegetation types has been refined and standardised over many years and applied consistently across geothermal sites within the Waikato Region, with the result that vegetation types and their areas have been inventoried to a high standard. Detailed mapping of vegetation types and their areal extent was a component of 12 of the reports in our literature survey, including several region-wide complementary surveys (e.g., Wildland Consultants 2014).

Consenting conditions associated with the extraction of geothermal energy have generally focussed on the biodiversity values associated with sites likely to be impacted and have aimed to ensure those values are adequately monitored. This monitoring is fairly prescriptive and aims to generate quantitative data that describes the condition of geothermal vegetation and flora, although often the purpose of this monitoring is vague and the consent condition being applied is simply 'monitoring' rather than assessment against some type of compliance trigger.

Monitoring of geothermal ecosystems to date has provided reliable baseline information on presence, abundance, and distribution of threatened species and on geothermal vegetation types and extent. Weed invasions have been monitored and results clearly indicate the adverse effect of weeds on geothermal areas. Conversely, the effect of good weed control has been shown to provide quantifiable benefits to geothermal vegetation. Changes that have been identified in monitored geothermal areas include:

- A general increase in the distribution and abundance of pest plant species.
- Changes in cover of geothermal vegetation and the extent of different geothermal vegetation and habitat types.
- Increases in geothermal kānuka height at some sites.
- Loss, decline, and recovery of geothermal vegetation after weed-spray damage occurred.
- Overall decline in 'geothermalness' (see Section 6.4 for definition).

Detailed monitoring of unusual and threatened plant species in geothermal areas provides valuable information that could be used to inform management of these species.

6.2 Approaches to monitoring

Overlaying these differences of purpose suggest changing trends in monitoring approach over time. Seven broad approaches to data collection for the purposes of monitoring or otherwise assessing geothermal ecosystems have been applied. These broad approaches to monitoring are not mutually exclusive. Contemporary site-specific monitoring programs may involve a combination of qualitative description, photo points, mapping of vegetation types from aerial photography, and quantification of vegetation structure and composition using Scott height grids. Further, recent studies have included emerging technologies such as drones in an experimental manner for site mapping. These were not included as part of this historical review but are considered below.

6.2.1 Qualitative appraisal

Early description and monitoring of geothermal ecosystems was predominantly qualitative. The most common method was to enlist the services of people with relevant expertise who would then conduct walk-through surveys of sites of interest and provide a qualitative assessment of vegetation composition and condition. This approach to scientific description of geothermal ecosystems has been applied since 1859 (Hunt *et al.* 1994) and was used to assess consent conditions alone as recently as the late 1990s and in combination with vegetation mapping using GIS and aerial photography as recently as 2021. Twenty of the reports included in our study included a qualitative description and assessment of vegetation condition sometimes complemented by photo points, which contributed an element of verifiability to the observations reported and allowed informal reporting to better accommodate changes through time.

6.2.2 Photopoints

Photographs are taken from known locations (photopoints) over several years to provide a visual record of changes in vegetation over time. Geothermal sites with photopoint monitoring currently have between seven and 21 photopoints. Over time, some photopoints have become less relevant, blocked by growing vegetation, unsafe or difficult to access. In such situations, additional or replacement photopoints have been established.

6.2.3 Grid-based transects

Since the late 1990s monitoring of geothermal vegetation has shifted toward the collection and analysis of quantitative data on vegetation structure using Scott height poles (Scott 1965). Though used in vegetation monitoring, particularly scrub communities, in New Zealand since 1965, it was the monitoring report of Burns *et al.* (1996) and the seminal publication by Burns (1997) on the relationship between geothermal vegetation and soil temperature that established this and its application on a 1 m square grid as the approach of choice for monitoring geothermal vegetation condition. This preference persists to the current day. Twelve of the papers and reports in our literature survey employed vegetation measurement using Scott height poles on a grid (Appendix 2) either along a gradient from cool to hot geothermal ground, or wherever they could be established within a site.

Because of the strong correlation between above-ground vegetation and ground temperature noted since the 1960s (Dawson 1964, Hochstein & Dickinson 1970, Vucetich & Wells 1978, Burns 1997), grid-based vegetation monitoring studies undertaken since the late 1990s have included temperature measurements at a depth of 10 cm or 15 cm. Twenty-three of the 51 reports in our review included measurement of geophysical properties, almost all of which were subsurface soil temperatures. Soil temperature is recorded using a thermometer at 0-10 cm deep (depending on the hardness of the substrate) every 1 metre along each transect at the same points where vegetation is measured. These temperature measurements can then be correlated with the vegetation present to identify trends. Temperature measurements are not designed to measure the ground temperature of the site *per se* but are useful covariates that may help explain geothermal vegetation patterns. Additional soil temperature readings at 40 cm depth (at 5 metre intervals) were recorded during the most recent monitoring surveys at four monitoring areas, to assess temperature change where it is less influenced by short-term fluctuations (e.g., daily, or hourly) in surface temperature and solar radiation. At some points, substrate impenetrability precluded subsurface temperature measurement.

6.2.4 Fixed-area plots and RECCE method

Fixed-area plots and associated estimates of cover abundance using the Relevé or RECCE method (Allen 1979; Allen and McLennan 1983; Hurst and Allen 2007) have been incorporated into some research projects and consent monitoring programs. Within geothermal areas, the first transects were established by Given (1980), who also cleared vegetation from several 3 × 3 metre plots to assess recolonisation rates. Permanent plots to measure the structure of natural vegetation in geothermal areas were evidently first established at Karapiti by three bryologists, Zen Iwatsuki, Janice Glime and Jessica Beever in 1988, and remeasured in 1989 as part of a project on geothermal bryophytes worldwide, results of which were published in part. These plots were remeasured by Burns *et al.* (1996). Plot-based vegetation description was used in eleven of the papers and reports in our literature review, with plot sizes ranging from 0.2 × 0.2 m to 20 × 5 m (Table 2). In all but one study, plots were replicated to some degree (two or more plots measured per site).

Table 2 A selection of studies including fixed-area plots, with plot dimensions and replication indicated, illustrating variation among studies

Study	Plot Dimensions	Within-Site Replication
Burns *et al.* (1996)	0.2 × 0.2 m	Yes
Wildland Consultants (2009b)	20 × 5 m	No
Wildland Consultants (2015b)	1 × 1 m	Yes
	3 × 3 m	Yes
Wildland Consultants (2016)	0.5 x 0.5 m	Yes
	1 × 1 m	Yes
Wildland Consultants (2019a)	0.5 × 0.5 m	Yes
Wildland Consultants (2019b)	10 × 10 m	Yes
Wildland Consultants (2019c)	0.5 × 0.5 m	Yes

6.2.5 Mapping the spatial extent of geothermal vegetation

The advent of Global Information System technologies, advances in the quality and resolution of aerial photography, and the regular capturing of aerial photographs led to the development of the inventory of vegetation communities and their extent. This inventory grew from earlier efforts to standardise the recognition and description of vegetation communities in New Zealand (Atkinson 1985). Twenty of the 51 studies included mapping the spatial extent of sites and their constituent vegetation types. Mapping of geothermal vegetation extent and type has been completed and regularly updated for all geothermal sites in the Waikato Region as part of monitoring to detect changes in the extent of geothermal vegetation throughout the Waikato Region (Wildland Consultants 2014). The quality of aerial photography has improved over the years, which has in turn improved the mapping of vegetation boundaries and the estimation of area of both vegetation types and sites. Field visits have not always coincided with the aerial photography used in assessments.

6.2.6 Monitoring of Threatened and At Risk and geothermal indicator plant species

Monitoring of Threatened and At Risk plants and geothermal indicator plant species may provide evidence of a vegetation response to changes in geothermal activity. Examples of geothermal indicator species include:

- Geothermal kānuka (*Kunzea tenuicaulis*)
- Dwarf mistletoe (*Korthalsella salicornioides*)
- *Christella* sp. aff. *dentata* 'Thermal'
- *Cyclosorus interruptus*
- *Dicranopteris linearis*
- *Nephrolepis flexuosa*
- *Psilotum nudum*
- Arrow grass (*Triglochin striata*)
- *Lycopodiella cernua*

For each species, population size and age structure, health and fertility were recorded, and an assessment of threats including animal browse and pest plants, made to aid management recommendations.

6.2.7 Monitoring of fauna

Birds have been recorded incidentally in four reports. Generally, the spatial and temporal bounds to listing of birds were not stated.

Pest animals have been included in only one study, in which pest animal sign (for example, footprints or excrement) was recorded where it was encountered.

Studies of macroinvertebrate extremophile communities were summarised by Boothroyd (2009). Extremophiles may be informative indicators of ecosystem condition, if for example they are more sensitive to change than geothermal vegetation, and to identify the extremophile species pool from which potential indicator species could be drawn.

6.3 Extent of monitoring

Quantitative monitoring with structured establishment of plots or grids and their repeated remeasurement has occurred as a result of resource consent conditions for geothermal energy extraction. There is, therefore, a bias towards development geothermal systems where monitoring currently occurs. There is no comparable monitoring of protected geothermal systems.

Quantitative plot-based monitoring occurs in 12 sites in the Waikato Region (Table 3). Of the 12 sites with plots or grids, only four are less than 10 ha in size (33%) (Table 3). Of the 64 geothermal sites in Waikato, 46 (72%) are less than 10 ha in size, so smaller sites are under-represented in existing monitoring. This could potentially mask a general decline in condition across geothermal sites, if smaller sites are more susceptible to degrading processes such as weed invasion.

Table 3 Sites with geothermal vegetation in which plot- or grid-based monitoring has been established (based on Wildland Consultants 2016a, b).

Site Name	Geothermal Vegetation (ha)	Site Area (ha)
Tirohanga Road	0.2	0.5
Pareata Road	1.7	1.8
Te Kopia	58.8	59.9
Orakonui	1.5	1.7
Ohaaki Steamfield West	11.7	11.8
Broadlands Road	29.8	29.8
Crown Road	17.5	17.5
Upper Wairakei Stream (Geyser Valley)	4.7	4.7
Te Kiri O Hine Kai Stream Catchment/Wairoa Hill	40.1	40.3
Craters of the Moon	44.6	44.6
Rotokawa North	34.3	34.4
Lake Rotokawa	69.4	137.3

Of the 64 geothermal sites in the Waikato, nine have soil and water temperature records; 12 have vegetation plots or transects; 15 have photopoints; and 48 are known to have Threatened and At Risk plant species, for which population monitoring is undertaken at 13 sites (Appendix 3, Wildland Consultants 2016a, b).

6.4 Geothermalness

This term describes the level of the geothermal character of the vegetation, based on the species present and their growth form. This includes representative species typical of geothermal habitat and the form of the vegetation, e.g., low sprawling geothermal kānuka is more typical of sites with high geothermal activity than taller upright geothermal kānuka. Sites that are said to have declined in 'geothermalness' tend to have fewer species typical of geothermal habitats and taller growth forms. These changes are typically measurable and 'geothermalness' has been used as a monitoring indicator at sites within the Wairākei Geothermal Field (Wildland Consultants 2017). Correlation between above-ground vegetation and ground temperature has been noted since the 1960s (Dawson 1964, Hochstein & Dickinson 1970, Vucetich & Wells 1978) and was described most fully by Burns (1997) at Te Kopia where a strong relationship was found between vegetation and soil temperature at a depth of 15 cm. Given (1980) showed a clear pattern from low to high 'geothermalness' of vegetation with increasing soil temperature at Karapiti (Craters of the Moon). The extent and composition of geothermal vegetation is closely linked to high soil temperatures, which limits rooting depth and excludes many species that are intolerant of higher temperatures. There is usually a complete lack of vegetation where soil temperatures at 5 cm depth are over 97°C, lichens and mosses are dominant where soil temperatures are 60-70°C, and vegetation dominated by geothermal kānuka occurs where soils are 40-55°C. Where soil temperatures are less than 40°C, indigenous species such as whauwhaupaku (*Pseudopanax arboreus*) and exotic species such as radiata pine (*Pinus radiata*), broom (*Cytisus scoparius*) and blackberry (*Rubus fruticosus*) become increasingly common.

6.5 Indicators

A suite of simple and accurate indicators were recommended by Wildland Consultants to assess extent, condition, and landscape context of geothermal vegetation in the Waikato Region (Wildland Consultants 2015). These indicators, which are measurable, precise, consistent, and sensitive, build upon the mapping and quantification of vegetation types, plotting methods, and rare and threatened plant surveys that are all part of the broader monitoring programme currently implemented on geothermal ecosystems in the Waikato Region. Metrics recommended by Wildland Consultants (2015) are:

- EXTENT
    - Area of identified geothermal Significant Natural Areas (SNA)
    - Area of legally protected geothermal SNA
- HABITAT RICHNESS
    - The number of geothermal habitats
- CONDITION
    - Indigenous dominance
    - Vegetation and habitat structure and composition
    - Characteristic species and richness
    - Threatened and uncommon species
    - Direct human activity
    - Pest plants
    - Pest animals
- LANDSCAPE CONTEXT
    - Connectivity and buffering
    - Landscape pattern
    - State of hydrological regime

Condition of geothermal sites can be assessed in terms of the number of habitats (whether defined with reference to a standard classification such as Smale *et al.* (2018) or the actual character of vegetation as assessed on site) and indigenous dominance of the vegetation. Indigenous dominance has two components, structural dominance and diversity dominance. By measuring the relative area dominated by indigenous species and the proportion of indigenous versus exotic species present at each site, these two indicators contribute to the measurement of ecological integrity.

Plot-based metrics describing vegetation structure and composition structure can be assessed against an optimum or baseline level. One example used for geothermal vegetation is the biomass index, a sum of the frequency of each species within 10 cm height intervals, to statistically compare changes in vegetation structure through time (Merrett and Burns 1998).

Presence of plants characteristic of geothermal vegetation and of threatened and uncommon species have also been used as indicators of condition, including the number of areas where these species are present, and population demographics for each taxon if population size and structure is quantified. Pest plant presence, cover, and abundance within sites is also a good indicator of condition.

The metrics recommended by Wildland Consultants (2015) are usually bounded by vegetation type or site, which may change through time. Metrics are not often replicated at a site level. Variation among observers as a function of differing background knowledge, skills and experience introduces a degree of subjectivity to most metrics. Sampling effort is rarely quantified; the number of species recorded at a site is related to the amount of search effort (Azovsky 2011), so differences in species richness may result from differences in effort.

This suite of indicators currently used to assess the condition of geothermal vegetation is much broader than those derived from the standardised methods for monitoring ecological integrity proposed by Bellingham *et al.* (2021). However, an assessment of vegetation condition in terms of indigenous dominance measured as relative cover is common to both sets, as is the occupancy of species or species groups associated with particular habitat types. Extent of ecosystems, which is currently measured as part of Waikato Regional Council monitoring, is a critical component of ecological integrity (Bellingham *et al.* 2021).

The key difference between the metrics proposed by Wildland Consultants (2015) and Bellingham *et al.* (2021) is how those metrics are collected, with Bellingham *et al.* (2021) advocating methods that maximise objectivity and enable sampling and measurement error associated with measurements to be both minimised and estimated. This allows estimates to be analysed against regional and national trends.

There is, then, an opportunity to maximise the benefit derived from incorporating monitoring compatible with the biodiversity monitoring framework into the monitoring programs currently used within the Waikato Region. The benefit has two components: first, including a nationally rare ecosystem type within the National Biodiversity Framework; and second, quantifying their ecological integrity.

6.6 Summary

Over 22 years of monitoring, the results of the monitoring programmes for resource consent conditions (Table 4) have not triggered any non-compliance actions, i.e., no thresholds within the consent conditions have been exceeded (noting that some of the consent conditions specify that wetlands be ‘monitored’ without mention of compliance thresholds). This is in spite of a general acceptance that energy extraction (at least using earlier technology) does alter geothermal habitats and features, and that changes in geothermal vegetation have been measured during monitoring. However, linking changes in geothermal vegetation to energy extraction remains difficult and there are multiple complicating factors to deal with, many of which are summarised in Section 7 below. These complicating factors, and long-term monitoring experience, should be used to inform any future monitoring programme that is developed.

Table 4 Summary of methods used for monitoring the effects of geothermal energy exploitation at eight sites (from Beadel *et al.* 2020).

		Site							
		A	B	C	D	E	F	G	H
Method	Vegetation mapping	✓	✓	✓		✓			✓
	Geothermal indicator plant species	✓	✓						
	Number of photopoints	10	7	11	17	18	7	10	21
Layout of Monitoring Grids	Number of permanent monitoring grids	4	4	2	4	0	7	4	6
	Number of RECCE plots	0	1	2	4	0	7	0	0
	Number of transects	4	3	8	20	0	0	4	6
Methods Used Within Transects	Soil temperature at 10 cm depth	✓	✓	✓	✓		✓	✓	✓
	Percent cover of each plant species	✓	✓	✓	✓			✓	✓
	Scott-height frequency			✓	✓		✓		✓
Data Analysis	Comparisons of data between years and monitoring grids	✓	✓	✓	✓		✓	✓	✓
	Comparisons of indicators of geothermal vegetation health						✓		
	Comparisons of number and identity of plant taxa recorded	✓	✓	✓	✓	✓	✓	✓	✓

7 Key considerations when monitoring geothermal sites

In Section 5, systematic biodiversity monitoring is defined as monitoring underpinned by a statically valid selection of monitoring plots, sites or locations; establishment of strict data collection protocols; and characterised by repeat measures. When designing such a monitoring system for geothermal sites, a range of factors must be considered, many of which will limit one or more of the factors associated with this definition.

7.1 Intrinsic ecological factors

7.1.1 High diversity of vegetation and habitat types and structural classes

In terms of naturally rare ecosystems, five key geothermal types are recognised (Williams *et al.* 2007, Holdaway *et al.* 2012, Wiser *et al*. 2013): acid rain ecosystems, hydrothermally altered ground, geothermal streamsides, fumarole's, and heated ground[1]. In our opinions, geothermal sites are considerably more diverse than these five types suggest, and one major type, permanent geothermal wetland habitat, is missing in this assessment. The complexity of some of the factors naturally affecting the nature and distribution of biota at geothermal sites is shown in Figure 1. Some types, e.g., alpine geothermal habitats, are particularly rare.

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[1] https://www.landcareresearch.co.nz/publications/naturally-uncommon-ecosystems/geothermal: accessed 17 February 2022.

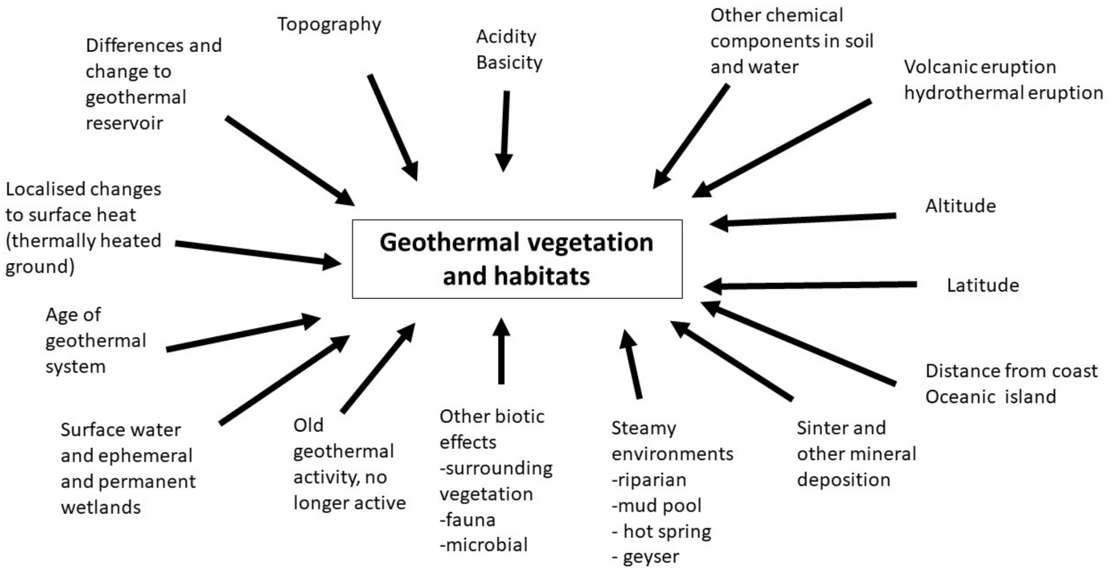

Figure 1: Key factors that contribute to the character and composition of vegetation and habitats at geothermal sites.

The picture becomes more complex when human induced impacts are overlain as shown in Figure 2.

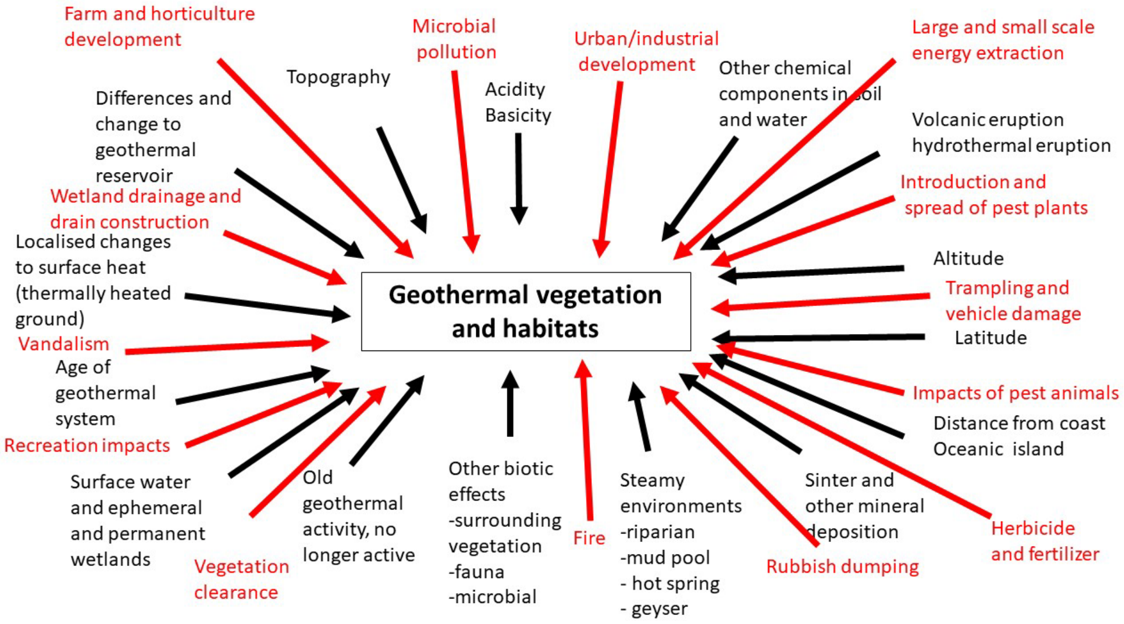

Figure 2: Key natural factors with key compounding human induced factors that can affect/impact on the character and composition of vegetation and habitats at geothermal sites.

7.1.2 Naturally dynamic sites

A complex suite of processes including changes in geothermal activity, vegetation succession and pest plant invasion drive changes in the structure and distribution of the vegetation in geothermal ecosystems.

Some of the challenges for both monitoring and indicators might be conceptualised with the aid of a simplified, and hypothetical, model describing the relationship between geothermal activity – which influences soil temperature and soil chemistry – and vegetation response. For simplicity, consider a level site with a geothermal hot spot at its centre. Within the hot spot the soil temperatures are too high to support vegetation so the ground is bare. Around this bare central area is a zone of thermally heated soils supporting thermotolerant vegetation. Outside of this zone the soils have cool to ambient temperature and support indigenous vegetation typical of normal soils (Figure 3). The soil temperature profile, and the size of the central bare area are determined by the level of geothermal activity. If the activity increases, so does the amount of bare ground at the centre of the site, at the expense of existing geothermal vegetation which is killed by lethal soil temperatures there. Geothermal vegetation subsequently expands into the surrounding forests as they are killed by the correspondingly higher soil temperatures underneath them. Under the scenario of an increase in geothermal activity, it might be expected that the area of geothermal vegetation would decline initially as a result of death along the inner perimeter before increasing in area as it expands along the outer perimeter. Conversely, if the amount of geothermal activity declines, so does the soil temperature profile, which contracts toward the site centre. Some of the bare soil at around the centre of the site is colonised by geothermal vegetation. This expansion along the inner perimeter of geothermal vegetation may be rapid, involving lateral growth and seedling establishment on bare ground, and may be complete within a few years. Meanwhile, mature, tall geothermal kānuka remain standing with a closed canopy on now cool soils along the outer perimeter. It may be decades before they senesce and die, to be replaced by successional broadleaf species able to grow on what was previously geothermally heated soil (now cooled, it will remain geothermally altered for decades at least). The initial spatial response to a reduced soil temperature profile may be an increase in geothermal vegetation cover, which is the opposite of the longer-term trend which might not be realised for some decades.

In both scenarios of change in soil temperature profile in this simplified model there is an initial spatial response by geothermal vegetation which is opposite that of the long-term trend, in other words a lag, because of differential vegetation responses along the inner and outer perimeters of geothermal vegetation in combination with the perimeter effect itself. As the inner perimeter is smaller than outer perimeter, any contraction of geothermal vegetation toward the centre results in greater loss of area at the outer perimeter than is gained at the inner.

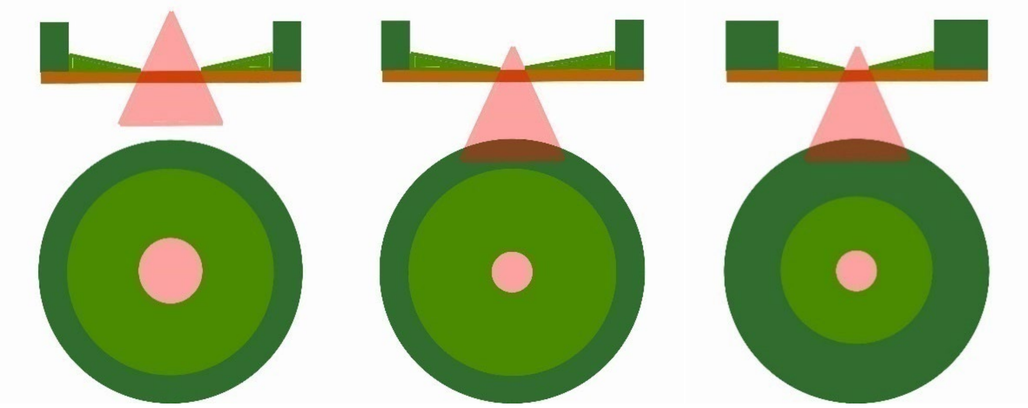

Figure 3. A simplified hypothetical model of geothermal vegetation response to reduced surface activity. Pink is a 'cone' of geothermal heat and associated bare geothermal ground, light green is geothermal vegetation, and dark green is non-geothermal vegetation. The pre-existing state is at the left. The figure shows two hypothesized phases in vegetation response to reduced geothermal heat. The first phase (middle) is colonisation of previously bare ground while hydrothermally altered soils around the periphery of the site remain dominated by geothermal vegetation. The second phase (right) is succession on hydrothermally altered and now cool soils with associated loss of geothermal vegetation.

At some geothermal sites, isolation from indigenous seed sources may be facilitating succession dominated by exotic weeds.

7.1.3 Temperature variation on small spatial scales

Strong abiotic gradients may occur over very small spatial scales, for example within an area of 0.5 × 0.5 m as observed at Parimahana (Wildland Consultants 2018a). These gradients drive the diversity of vegetation pattern referred to in the sections above.

7.2 Other constraints

These intrinsic ecological factors interact with several other critical factors that together present significant challenges to the design of a monitoring framework for geothermal ecosystems compatible with the National Biodiversity Monitoring Framework.

7.2.1 Dangerous sites

Geothermal sites are inherently dangerous, and thus plots cannot be placed randomly without consideration of safety factors. Almost all sites in the Waikato Region have parts which are inaccessible because they are too hot, the ground surface is too unstable, and/or there is a risk of suffocation from the accumulation of hydrogen sulphide and carbon monoxide in hollows and low-lying areas. The dynamic nature of geothermal sites means that these dangers can change between assessments, and this can affect remeasurement of plots.

In addition to affecting the random placement of plots, the heightened danger of some particular habitat types (e.g., dangerous ground alongside springs, geysers, and geothermal streams) affects the ability to include all vegetation types and habitats in an inclusive monitoring structure.

Danger can also mean different things to different people. One team may be relatively comfortable monitoring an area that others deem unsafe. This subjectivity will also affect the randomisation of a monitoring programme, and how data are subsequently dealt with, e.g., if plots are abandoned because they are deemed too risky to sample.

7.2.2 Impacts of monitoring

Monitoring can unintentionally alter the vegetation and habitats present by physically modifying the habitat through trampling damage and compression of substrate over long periods of time. Burns *et al.* (2013) demonstrated a significant impact of trampling on soil compaction, which was associated with significantly lower cover and height of indigenous vegetation at the track edge. Experimental trampling treatments were applied at Taheke, comprising 20 lanes measuring 1.5 by 0.5 m. Each lane was assigned to one of five treatments: 0, 25, 75, 200, or 500 passes. Burns *et al.* (2013) demonstrated significantly higher penetration resistances in lanes receiving 200 and 500 passes, with penetration resistance reaching 2000 kPa after 500 passes. Treatments of 25 to 75 passes resulted in modest increases in penetration resistance, around 15-25% (based on Figure 6 in Burns *et al.* 2013).

Vegetation cover also decreased with trampling, with above-ground cover declining progressively with increasing trampling to 20% or less on average at 75 passes and remaining constant with increased trampling. The amount of trampling required to reduce vegetation cover by 50%, the vegetation ‘resistance index’ of Liddle (1997), was estimated at 51 passes for ground cover and 174 passes for above ground vegetation. Though they did not assess vegetation recovery following trampling, Burns *et al.* (2013) suggested that geothermal vegetation would probably recover slowly due to the naturally slow growth rates of the species present (Burns and Fitzgerald 2007).

Hill and Pickering (2009), in a study conducted in non-geothermal vegetation in eastern Australia, found that the fern-dominated understoreys in *Eucalyptus* dominated wet-sclerophyll forest were most susceptible to the immediate impacts of trampling, with relative vegetation height within the ground layer significantly reduced after just 10 passes, and a 50% reduction in height after 90 passes. Before trampling there was significant overlapping ground cover, which was significantly reduced at even the lowest trampling levels. Species richness in the fern-dominated understorey declined with increased trampling intensity, with significant decline again after 10 passes, probably due to damage to small, fragile herbs including *Corybas* spp. and *Eustrephus* spp. Hill and Pickering (2009) suggested that fern understoreys would have low resistance and low tolerance of trampling due to the probable slow recovery of this community. These trampling treatments were applied to a fern community dominated by *Pteridium esculentum* which may be more resilient to trampling than some other ferns associated with geothermal areas, due to its coriaceous foliage and robust rhacis, both of which resist crushing. The variety of vegetation types in geothermal ecosystems, including shrublands, wetlands, mossfields and soilfields, are likely to have different susceptibilities to trampling. For example, geothermal wetlands would be expected to be more susceptible to trampling damage than raw geothermal soilfield. However, the impacts of monitoring activities on geothermal ecosystems have not been quantitatively monitored, although sites experiencing biennial monitoring appear to have no impact from previous monitoring activities (C. Bycroft *pers. obs.*).

The findings of these studies of vegetation response to trampling have implications for the implementation of ground-based monitoring in geothermal vegetation, in that it should be slow, deliberate, and completed in a single pass to minimise the impacts of foot traffic on vegetation and soils. Geothermal vegetation may be able to withstand annual monitoring if it is conducted sensitively, and this should be established by assessing damage and recovery of vegetation occurring in monitoring-like trampling treatments. The biggest knowledge gap is related to the rate of recovery of different kinds of geothermal vegetation and habitats following varying degrees of trampling impact, and particularly relatively low-intensity trampling. Can all geothermal vegetation, habitats and soils recover fully from a low-intensity trampling during monitoring before the next monitoring event?

7.2.3 Permanent plot marking

Plot markers need to be permanent to ensure that plots are located in exactly the same place each monitoring round, but permanent plot markers can be inappropriate in some geothermal areas such as tourist venues. Steel pegs are not appropriate at geothermal sites because they rust quickly in this environment. Aluminium and stainless steel are generally more durable. The utility of modern composite materials such as carbon fibre has not yet been investigated. Wooden pegs (treated timber) often rot quickly and in some cases leach considerably into the surrounding soil, potentially altering soil composition. Fibreglass or aluminium poles have been used in recent years and along with carbon fibre poles, may be a good solution to the issue of plot marking, if they are tall enough and suitably coloured to be conspicuous.

7.2.4 Geothermal extraction

A monitoring programme for geothermal sites will need to consider the underlying geothermal resource. Extraction of geothermal energy and subsequent reinjection of geothermal fluids is likely to result in a geothermal field with different behaviour to a protected system, and this should be considered as part of the monitoring framework design.

7.2.5 Site history and historic land use

Some sites have been highly modified in the past and their current geothermal vegetation reflects this. For example, parts of the Rotokawa Geothermal Field were mined for sulphur. Monitoring to date shows a progressive increase in geothermal kānuka height in these areas. Without knowledge of previous site history, this could be considered a result of surface temperature changes but at Rotokawa this mostly reflects successional change following complete clearance of the original vegetation for mineral extraction.

7.2.6 Land access and cultural considerations

Some geothermal sites are on land for which access permission could be withheld. While this is the case for all monitoring programmes, the restricted number and extent of geothermal ecosystems means that lack of access could bias samples. A small number of sites have not been surveyed or monitored since the 1990s due to access permission being withheld, as is the landowner's right.

Some of the geothermal features within particular sites are wāhi tapu and hold special significance to Māori. Monitoring within these features must be either avoided or adhere to strict cultural protocols, affecting randomisation of plot placement. For example, no survey or monitoring has ever been undertaken at Ketetahi out of respect for cultural significance.

7.2.7 Abandonment of plots and subsequent treatment of data

Monitoring plots do get abandoned due to safety concerns and can also be abandoned when vegetation is no longer geothermal in nature. For example, a plot was abandoned at Rotokawa in 2021 due to part of the site being dangerous to measure and future access to the site is also dangerous due to unstable ground (Wildland Consultants 2021). In another example, a plot that is now covered in dense blackberry is not safe to measure because blackberry can obscure dangerous ground. The cover of blackberry also indicates that most, if not all, of the plot has cooled to an extent that blackberry can grow (although it should be noted, that blackberry can cover active geothermal vegetation if it spreads out from where it is rooted in less geothermally active areas nearby). A challenge of any monitoring programme is how to continue to collect information on sites which are not safe to measure, and how to deal with such sites in data analysis (as removal from the dataset may bias results).

7.2.8 Small sites

Thirty one of the 64 sites are less than 1 ha in size allowing only limited replication in them. Forty six of the 64 sites are less than 10 ha (Appendix 2). A sampling and data analysis strategy should ideally be capable of accommodating small sites, including those within which replication of sampling units is not possible.

7.2.9 Historical data collection

A monitoring design should recognise the long-term data sets that already exist and incorporate useful metrics from these where possible.

7.2.10 Data storage

Where the data should be stored is also a consideration of monitoring design. Storage in a dedicated facility, such as the NVS database at Landcare Research could be investigated.

8 Monitoring frequency

The key constraint on monitoring frequency is the susceptibility of geothermal sites to trampling impacts associated with monitoring. The minimum return time for remeasurement could be assessed by first establishing the resistance and resilience of different geothermal vegetation and habitat types to monitoring. Minimum monitoring frequency will also be governed by the purpose and costs of monitoring. Quantitative monitoring could occur less frequently than the qualitative monitoring currently being undertaken, if the purpose of quantitative plot-based monitoring is to complement the set of established indicators of geothermal ecosystem integrity. A marked change occurred at one site when herbicide spray drift from neighbouring land killed susceptible plants (e.g., arrow grass and geothermal kānuka) in several geothermal vegetation types. The cause of the damage could not have been determined if the monitoring period were longer.

9 Applying criteria of Bellingham *et al.* (2021) to methods for geothermal ecosystems

Geothermal ecosystems contain vegetation that varies in stature both among and within sites.

In situations of high structural diversity, Bellingham *et al.* (2021 p.13) suggest that "stratification could greatly influence sampling efficiency. In complex sites where multiple broad ecosystem groupings may be present, a site might be stratified according to vegetation height/structure, with different methods applied within them (e.g., foredunes, freshwater wetlands in the back dunes, old-growth forests further inland)."

For any given geothermal site up to four different plot sizes could be applied to capture the diversity of vegetation types under the Bellingham *et al.* (2021) protocol.

Forests and tall shrublands	20×20 m
Wetlands	5×5, 10×10 or 20×20 m
Perpetually herbaceous communities and short shrublands	2×2 or 5×5 m
Skeletal ecosystems on stable substrates	2×2 or 5×5 or 10×10 m
Ecosystems that are dangerous to sample.	no recommendation

The disadvantages of using different plot sizes across different ecosystems include that scale-dependent metrics such as species richness cannot be validly compared across plots of different size. This is a recognised issue and analytical methods facilitating species richness comparison across plot-based inventories using different plot sizes are being developed (e.g., Portier *et al.* 2022). Small plots are generally poor at sampling sparsely distributed species. A 10×10 m plot size across all ecosystems may provide a practical alternative and has been used successfully elsewhere in New Zealand in both forested (Tanentzap & Lloyd 2017) and non-forested (Wildland Consultants 2018b) habitats.

Because the focus of Bellingham *et al.* (2021) was on harmonised monitoring protocols, they did not address the issue of sampling design and plot location. There are, then, several considerations relevant to the design of a monitoring protocol for geothermal ecosystems, centred on two themes:

Theme 1: Sampling protocol. What should be done on the ground?
Theme 2: Sampling design. Where should it be done?

These considerations are discussed below. We discuss sampling protocol first because that may influence where sampling can occur within hazardous sites, such as geothermal areas.

10 Key consideration for monitoring protocols

An optimal protocol for quantitative plot-based monitoring that complements existing monitoring activities will accommodate all the considerations relevant to the monitoring program laid out above, as well as set out by Bellingham *et al.* (2021), from the overarching goals of monitoring to data analysis and interpretation. As part of the process through which monitoring protocol recommendations for geothermal ecosystems were developed, a range of key considerations were identified and discussed at a workshop whose participants included representatives from local and regional councils, the Department of Conservation, the university sector, ecological consultancies, and the geothermal resource user sector (see participant list in Appendix 3). This section presents a summary of the discussion that occurred during the workshop.

10.1 Theme 1. What should be done on the ground?

10.1.1 What are the goals of monitoring?

The goal of monitoring is to measure changes in ecological integrity through time, especially in response to management targeted at maintaining or restoring ecological processes. This is the goal of the Biodiversity Monitoring and Reporting System. But more than this, the goal of monitoring geothermal ecosystems is to ensure changes that may be associated with geothermal energy extraction can be detected and quantified or that conversely, confidence can be established that energy extraction is having no detrimental impact on geothermal ecosystems.

In terms of ecological integrity, the questions naturally arise: What is ecological integrity and what is it that is being measured? McGlone *et al.* (2020) provide some explicit guidance on how the assessment advocated by Bellingham *et al.* (2021) can be achieved, especially in the comparison between ecological health and ecological integrity. Whereas health captures the functionality of the species assemblage present at the site, regardless of its composition, integrity considers the species assemblage. These two components, what is there and how is it functioning, are both captured by ecological integrity, which is essentially a measure of whether what should be at a site is there and whether what is there is functioning as it should. Those assessments both imply a comparison either through time with a known historical state or, more realistically, other contemporary ecologically comparable sites whose ecological integrity is as intact as possible.

The assessment of ecological integrity should also be based on indicators outside of the Biodiversity Monitoring and Reporting System, including the extent of geothermal ecosystems, a measure that has been included in most monitoring programmes and which also measures occupancy of geothermal habitat. Ecological integrity is directly linked to another important consideration, which is how compatibility with monitoring data collected to date can be maximised.

10.1.2 Should geothermal sites be included within a national dataset?

There was broad agreement that geothermal sites should be included within a national dataset. However, the practicalities associated with achieving that goal are not clear, particularly the cost of collecting additional data from geothermal ecosystems to fulfil the requirements of the Biodiversity Monitoring and Reporting System, and who is going to pay for that data collection. These issues associated with the cost of data collection were not resolved, though the comment made by Bellingham *et al.* (2021) that as the resulting data exists for the benefit of all, there should be a cost-sharing arrangement on the same basis was noted.

10.1.3 Should the collection of quantitative data be the goal?

There was broad agreement that the collection of quantitative data should be a goal. The advantages of fixed-area based sampling advocated by Bellingham *et al.* (2021) were acknowledged by the workshop participants. Given that the approach to a biodiversity monitoring framework proposed by Bellingham *et al.* (2021) is based on permanent fixed-area plots, which have been widely used elsewhere in New Zealand, it follows that cover abundance data from geothermal ecosystems should also be based on permanent plots, for statistical conformity with the national data.

10.1.4 How should these sites be sampled?

The stratified approach of plot size selection by vegetation type suggested by Bellingham *et al.* (2021) was regarded as a suitable, achievable means to accommodate the diversity of vegetation types present within geothermal ecosystems, though it was noted that full measurement of 20×20 m plots was labour and therefore cost intensive. It may also not be feasible to fit full 20×20 m plots into some sites and geothermal habitats. The potential applicability of a 10×10 m plot size across all ecosystem types was considered, but for some systems the size of these plots presents the same challenges as larger plots, in that they are time-consuming to establish and remeasure, potentially expose a site to intense foot traffic and trampling, and may be limited by where they can be located in a geothermal area by their size and the need to not include active, hot and dangerous ground.

10.1.5 What options are there to maximise compatibility with historic data?

The existing monitoring programme in geothermal ecosystems, including the indicators currently recommended and used, does not need to be replaced by the protocol and data recommended as the basis for the Biodiversity Monitoring Framework. The existing suite of monitoring and indicators encompass a broader range of indicators of ecological integrity than those derived from fixed-area plots, including the area of ecosystem occurrence, a limitation of plot-based metrics which Bellingham *et al.* (2021) acknowledge. Compatibility with historical data will be maximised if established monitoring protocols are continued, with protocols for the biodiversity monitoring framework added on. Where redundancy exists and reverse-compatibility of datasets is established, some of the existing monitoring protocols could be discontinued.

10.2 Theme 2. Where should it be done?

10.2.1 What sampling strategy should be implemented to achieve adequate site-level replication?

Several options for plot selection were considered during the workshop. One option to ensure the full range of vegetation types present at a site are included in a sample set is to follow the recommendations for wetland habitats made by Bellingham *et al.* (2021), which follow the Clarkson *et al.* (2004, 2014) stratified random approach, whereby plots are randomly located within each vegetation type. At least one plot per vegetation type is measured. Within each vegetation type an excess of sample sites are randomly generated *a priori.* The sites are then visited in order and either measured, or if deemed too dangerous to measure excluded and the back-up sites are visited in sequence until the target number of sites has been measured. The practicalities of implementing this approach were discussed, and it was generally agreed this sampling strategy could be feasible to implement.

Other sampling strategies considered briefly included transect-based and purely randomised approaches to plot location. Both were generally regarded as undesirable because they could neglect rare vegetation types present at some sites.

10.2.2 What is adequate site-level replication for the purpose of monitoring ecological integrity?

This issue was acknowledged, but no firm proposals of what might be regarded as adequate site-level replication were made. Analysis of data can show when more replication is necessary.

10.2.3 How should small sites be accommodated?

There was some discussion regarding the challenges of replicating measurement of small sites, due to the impossibility of locating more than one plot, of any size in some instances, within them. There is no remedy to this situation, so an accommodation of small sites must then be achieved by data analysis. The lack of ability to replicate within small sites does not mean, however, that they should not be included within a monitoring framework.

10.2.4 How should dangerous sites be accommodated?

Drone technology was identified as a significant innovation that could allow dangerous sites to be sampled remotely. Imaging and digital technologies now linked to unmanned aerial vehicles means that high resolution orthorectified images of survey sites can be obtained. These images could potentially serve two purposes:

- first as a basis for collecting cover abundance data from plots from a birds-eye view which can be located within the images even if not permanently marked; and
- secondly, as a permanent record of the vegetation observed at the time of survey.

Depending on sampling strategy implemented, it may not be necessary to overfly an entire site, particularly if plots are located on transects. Surveys of the most dangerous sites by unmanned aerial vehicles may be particularly suited to geothermal ecosystems, as the most dangerous sites tend to be associated with lower-stature vegetation. This reduces the problem of assessing ground layers obscured by above-ground vegetation.

Other options for including dangerous sites include sufficient replication in safe habitats so that the exclusion of dangerous sites does not undermine measurement of ecological integrity at a site level, though this does have the drawback that a bias against vegetation associated with the hottest sites may be introduced into sample site measurement.

10.2.5 How should ecologically fragile sites be accommodated?

Fragility refers to the susceptibility of sites to human-induced damage, in particular trampling effects. Generally, the entirety of geothermal areas could be regarded as ecologically fragile, so they should be monitored in a manner that minimises their exposure to damaging impacts. More fragile habitats could be monitored at lower frequency, for example, partly compensated for by qualitative survey between quantitative monitoring events.

11 Mātauranga Māori perspective

A Mātauranga Māori approach to monitoring geothermal ecosystems involves overlaying a cultural lens to ensure that what is valued by iwi is protected and sustained, including sites of special interest and the health of geothermal areas themselves. It needs to be acknowledged that only a remnant of taonga tuku iho remains and what remains must be protected. Achieving those goals requires broader consultation between iwi and Waikato Regional Council.

Ngāti Tahu - Ngāti Whāoa has eleven geothermal fields within their rohe and have experienced a range of outcomes resulting from extractive use of geothermal fields, both good and not so good, and are therefore well placed to apply their past and current experiences to ensure better outcomes in the future. Ngāti Tahu - Ngāti Whāoa’s position is that cultural values must be acknowledged and respected. Monitoring to achieve that outcome, including measures, practices, and Waikato Regional Council responsibilities, within the Ngāti Tahu - Ngāti Whāoa rohe need to be established as part of a dedicated engagement and process with Ngāti Tahu - Ngāti Whāoa.

12 Monitoring options

The workshop participants provided some clear directions with regard to the approach to monitoring that should be taken when the Biodiversity Monitoring Framework is extended to geothermal ecosystems and also identified three key principles for any proposed monitoring program:

1) Compatibility with the Biodiversity Monitoring and Reporting System
2) Compatibility with historical monitoring of geothermal ecosystems
3) Applicable to the entirety of geothermal sites.

These principles guide our consideration of monitoring options.

12.1 Fauna

The proposed fauna monitoring methods recommended for birds, ungulates, lagomorphs, and predators are essentially the same across the six ecosystem types (Bellingham *et al.* 2021). For birds, two 5-minute bird counts encompassing a 100 m radius about a fixed point associated with each plot were recommended (Hartley 2012). For ungulates and lagomorphs, presence was sufficient, noted in the form of faecal pellets either within plots or along transects. For possums, chew card transects were recommended.

These approaches require standardising the sampling effort at minimal additional cost in some cases (birds), or the recording of additional observational data within plots in others (lagomorphs and ungulate pellets). The methods for possums require additional effort, but this is the only consideration required, given constancy of monitoring methods for these animals across ecosystem types. We regard these methods as established and focus in subsequent sections on options for monitoring geothermal vegetation. Terrestrial and freshwater invertebrate monitoring were not considered as part of this project.

12.2 Vegetation

For vegetation the Biodiversity Monitoring Framework (Bellingham *et al.* 2021) employs as a minimum the RECCE method (Hurst and Allen 2007 and updates) to obtain a full species inventory with an abundance value recorded for each species by height tier. We recommend the protocols of Bellingham *et al.* (2021) appropriate to the vegetation occurring within each plot be applied within geothermal habitats, though the plot sizes we recommend may be smaller. For example, forest and tall scrub within geothermal habitats would be measured using the protocol for forests but applied to a 10 x 10 m plot. The main departure from the Bellingham *et al.* (2021) methods we advocate is that, for all plots within geothermal vegetation, the percentage cover for all species within each height tier be recorded, rather than ordinal cover classes. We recommend this because percentage cover can be analysed in that format or converted to ordinal cover scores for comparisons with data collected on plots elsewhere, without loss of information content at the point of data collection. For plots in tall woody vegetation, additional measurements of stem numbers, stem diameters and ground cover are applied, following the methods of Bellingham *et al.* (2022) and Hurst *et al.* (2022). For smaller plots the collection of RECCE data only is recommended (with percentage covers being recorded instead of ordinal cover class), following the protocols in the Biodiversity Monitoring Framework (Bellingham *et al.* 2021).

12.3 Sampling unit

The sampling unit on which the biodiversity monitoring framework is based is a permanent fixed-area square plot, whose size may vary with vegetation type. Plots yield data whose statistical properties conform with the requirements of McGlone *et al.* (2020)'s definition of monitoring, which is employed by Bellingham *et al.* (2021). For compatibility, the extension of the monitoring framework to geothermal sites should be based on the same sampling unit, the fixed-area permanent plot.

12.3.1 Plot size

The standard forest plot size of 20×20 m (Hurst *et al.* 2022) strikes a balance between being small enough to practically measure yet large enough to sample all components of a forest stand, in particular tree density and diversity, within homogeneous vegetation (Bellingham *et al.* 1999). Most geothermal sites have shorter vegetation than tall forests, so a smaller plot size is appropriate.

Within the monitoring framework proposed by Bellingham *et al.* (2021) plot size varies with vegetation stature and pattern, with the largest plots, 20×20 m, recommended for forests, tall shrublands and herbaceous communities undergoing succession, following established practice; and smaller plots for non-woody communities including wetlands and herbfields on stable or mobile substrates.

Because much of the vegetation in geothermal ecosystems is dominated by woody species, it qualifies for measurement using 20×20 m plots, under strict adherence to the protocols recommended by Bellingham *et al.* (2021). However, there are three significant challenges associated with establishing 20×20 m plots within geothermal habitats. First, establishment of plots will not always be achievable due to the nature of geothermal sites, e.g., plots will necessarily be biased toward cooler 'safer' sites away from vigorous geothermal surface features. Second, where plots are established, they are likely to have significant impact on the vegetation on the plot due to the intense data collection protocols associated with the forest plot methodology (Hurst *et al.* 2022). Third, 20×20 m plots are expensive and may not be feasible given the cost associated with establishing and remeasuring large permanent plots in complex short shrublands. For these three reasons, feasibility, impact, and cost, we recommend that a smaller plot size be the basis of monitoring within geothermal ecosystems. The 20×20 m plot size is not well suited to geothermal habitats, given the challenges associated with moving around in them, the existence of strong abiotic gradients and small-scale spatial heterogeneity, the susceptibility of geothermal vegetation to trampling damage, and the cost. A smaller plot size will be advantageous from a logistical perspective, particularly if it is small enough to be measurable from a point, either a point at which the observer can stand or a point above which a drone-mounted camera can hover. This will limit movement of observers during plot measurement, and so reduce the impact of monitoring activities.

For the reasons stated above, we recommend the largest plot size established within geothermal ecosystems be 10×10 m, in forest and tall shrubland, with plots smaller than this in shorter stature vegetation. This was the approach taken by Smale *et al.* (2018) who obtained data on structure and composition using the Hurst and Allen (2007) RECCE method in plots ranging from 10×10 m in forest and tall shrubland to 2x2 m in short shrubland. The objective of Smale *et al.* (2018)'s study was vegetation type delimitation, rather than measurement of ecosystem health. Nevertheless, their deployment of different plot sizes across the breadth of geothermal vegetation structural diversity demonstrated that this approach, which is compatible with the way the Biodiversity Monitoring Framework deploys different plot sizes in different habitat types, can be used in geothermal ecosystems.

One option for extending the data collection into dangerous areas is to sample dangerous areas using the Biodiversity Monitoring Framework methods for skeletal ecosystems on mobile substrates. Many 1 m^2 plots could be measured to capture environmental gradients across dangerous areas. Because vegetation within dangerous areas is often of short stature, overflying a drone to obtain high-quality georeferenced aerial imagery upon which 1m^2 plots are located and measured would enable dangerous areas to be included within the Biodiversity Monitoring Framework. For small plots and high-quality imagery of short-stature vegetation it will be feasible to gather all required data. For dangerous sites covered by taller vegetation the same approach could be used, acknowledging the disadvantage that only the canopy or upper layer will be seen clearly. For long-term monitoring a record of canopy composition will still have value.

Compensation for the reduction in sampled area can be achieved by increasing replication, but in general this can only partly be achieved.

The smallest plot size recommended by the Biodiversity Monitoring Framework is 1×1 m for skeletal herbaceous communities, which have the lowest stature and smallest physical scale of vegetation pattern.

12.3.2 Plot size recommendation

The following plot sizes are recommended for terrestrial geothermal habitats:

Forest, tall scrub, and shrubland:	10 x 10 m.
Short scrub and shrubland:	2 x 2 m.
Mossfield and lichenfield:	1 x 1 m.
Raw soil field	1 x 1 m.

At each plot location, plot size could be scaled to suit vegetation stature if this changes over time. The advantage of flexible plot sizes is that they can be tuned to reflect vegetation stature and pattern in the event that replication at the plot level will miss relevant stand level parameters.

How plots should be located within geothermal sites is considered in section 12.4, below.

12.3.3 Plot shape

Protocols for the biodiversity monitoring framework proposed by Bellingham *et al.* (2021) are all based on square plots, regardless of plot size. This ensures methodological consistency in data collection across monitored vegetation types. While square plots are well established within New Zealand as a basis for vegetation monitoring protocols, circular plots are an alternative plot shape that could be used in geothermal ecosystems, and it is worth considering its advantages over square plots and investigating its compatibility with data from square plots within the context of analyses based on the national data set.

Square plots have four points controlling plot boundaries, each of which can be subject to location or relocation error, and the perimeter of the plots may also be subject to error even if the corners are marked. For square plots, there are at least four ‘free’ parameters associated with plot location, or more if some corners are unmarked.

The boundaries of square plots can be sighted along and delineated more easily than a circular plot, and cover may be more easily estimated in a square plot. In practice, laying boundaries over uneven terrain and within closed vegetation can be a source of remeasurement error when decisions regarding what stems to include or exclude need to be made during plot layout (Paul *et al.* 2019).

By contrast, circular plots have a single control point and a smaller perimeter for a given area than square plots, meaning fewer decisions on the inclusion or exclusion of plants, stems and trees need to be made (Paul *et al.* 2019). If the centre of circular plots is permanently marked the only ‘free’ parameter is the plot perimeter, which can be accurately and repeatably established by measuring the radial distance from the centre point, even if this involves many measures to the perimeter during the course of measuring a circular plot to confirm its boundary. In practical terms, the utility of circular plots is that there is only a single point to relocate for plot remeasurement. This could also be a disadvantage to plot relocation if the plot marker is lost. Establishment and relocation error may be lower with circular plots than square plots, and circular plots will be quicker to establish than square plots. The first advantage was sufficient for Paul *et al.* (2019 p.387), in a study comparing estimates of emergent tree density from square and circular plots, to recommend that 'Except in very large- scale plots, circular plot designs are generally superior to square or rectangular plot designs for the collection of quantitative and area-related ecological data because plot boundaries can be established by directly measuring distances to plot centre, and directional layout decisions are not required.' However, the systemic biases associated with square plots identified by Paul *et al.* (2019) are not likely to manifest within geothermal vegetation, and for consistency with established methods we recommend square plots be used.

12.4 Sampling strategy

For any given site there are a range of sampling options that achieve spatial balance and an unbiased sample that are, in theory, applicable to geothermal ecosystems. The practicality of their implementation and their potential adverse impacts are key factors involved in selecting among alternatives. A precondition of statistical sampling is that every member of a statistical population has the same *a priori* probability of being included in a sample. As with all sampling strategies, the range of options for obtaining unbiased samples falls into three established categories which are considered in turn: random, stratified random, and regular sampling.

12.4.1 Random sampling

Selecting plot locations using pseudorandom number generators represents an ideal strategy to achieving a representative, balanced sample of plots at a site. The advantages of this approach in the context of geothermal ecosystems must be weighed against the practicalities of implementation. From the implementation perspective, random sampling is likely to maximise the distances that must be travelled across geothermal ecosystems between sequential plots, which is undesirable in this ecosystem. This will especially be the case during the establishment phase of monitoring, if standard approaches to plot selection involving a predetermined list of locations is used and worked through until the requisite number of plots have been set up. The greatest drawback to a purely randomised plot selection strategy is that it will maximise foot traffic across a geothermal site. Other drawbacks are that rare habitat types are less likely to be included within a plot network based on random sampling.

12.4.2 Stratified random sampling

One approach to ensure that rare vegetation types are included is to use stratified random sampling, wherein habitat types are mapped for the purposes of sampling ahead of time, and plots allocated to each, usually in proportion to area with larger habitat types receiving more plots. The basis of a mapping for the purposes of sampling could be a standard vegetation classification system, such as that proposed by Clarkson *et al.* (2004) for wetland habitats, or an aggregation of vegetation and habitat types mapped as part of geothermal inventory surveys (Wildland Consultants 2005, 2014) based on structural and compositional attributes. However, the mapping upon which samples are stratified must include rare and uncommon vegetation and habitat types that are found in geothermal ecosystems, to ensure they are included within the sample of plots. Plots are then located within habitat types at random. This approach also maintains spatial balance and representativeness within the sample set. However, like random sampling, a stratified random sampling strategy will involve a lot of movement across geothermal sites, especially during the establishment phase. In the longer term, the benefits of stratified random sampling's balance and representativeness may be reduced or lost, because vegetation boundaries can shift and vegetation types can change within these dynamic areas. This is especially the case if centres of geothermal surface activity move, as they are known to do. The outcome is that as some vegetation types may become over or under-represented within the plot network, and rare vegetation types may be lost from a sample.

12.4.3 Regular sampling

Regular sampling is based on a known and predetermined rule which governs plot location. These rules dictate that plots be regularly arranged, either on grids or on transects which may, or may not, have a random origin. Regular sampling along transects rather than grids may minimise ground impacts from monitoring by reducing distances travelled between plots and allow plots to be measured in a single pass. Transects are unlikely to capture rare habitat types unless they are deliberately orientated to do so, but this strategy could also suffer longer- term effects of the inherent dynamism of geothermal habitats.

Because linear transects of plots minimise travel times, they will be cheaper to establish and remeasure, and have less impact on the geothermal site than other sampling strategies. Replication along a transect can be increased if required by reducing the distance between plots.

For plots along transects, marking each plot is desirable so that re-measurement error associated with plot relocation is uniformly distributed across the sample set or ideally, minimised entirely. On plots along transects whose ends only are marked, there is the possibility that plot relocation error is skewed toward the middle of the transect, where deviation of the transect either side of the original line is likely to be greatest.

Two transects could be arranged to traverse a site from north to south and from east to west, with their intersection on the hottest part of a site. This would allow replication across the habitat gradient from the coolest to the hottest soils. Alternative, depending on the time plots take to measure, two or more transects could be located to traverse a site at regular intervals. An office-based assessment such as using GIS software could be used to test whether or not this will reduce travel distances relative to those involved in random sampling.

This form of transect sampling is similar to a gradsect approach (Wessels *et al.* 1998), whose aim is the detection of the maximum number of species, rather than the representative sampling of areas for the purposes of analysing changes through time. Because neither guarantees that the full diversity of habitats will be adequately represented within a sample for the purposes of analysing and detecting changes through time, we do not recommend regular sampling based on transects for geothermal monitoring.

12.4.4 Sampling strategy summary

Different sampling strategies have advantages and disadvantages within the context of geothermal areas. Regular or random sampling may or may not capture all habitat types including those that are transitional among different structural classes.

In short shrublands and other low stature vegetation, plots will need to be a set minimum distance apart to ensure they remain discrete if vegetation stature increases.

A stratified random sampling strategy based on the area of different vegetation types, and as employed by the Biodiversity Monitoring Framework for wetlands, would be appropriate for geothermal areas. Plots could be accessed and measured on foot, except in areas deemed dangerous. In dangerous areas plots could be located and measured from aerial images.

12.5 Study design

Site selection is intimately tied to the goals of the monitoring program. Is the goal to include all sites, a representative sample of sites, or a targeted selection of just a few sites in order to address monitoring objectives? Monitoring of geothermal ecosystems should be undertaken to fulfill two objectives; first, measurement of their ecological integrity and secondly, to establish whether or not there is an effect of geothermal energy extraction or other human influence and if there is, the nature of that effect. The number of sites to which biodiversity monitoring framework methods are added will depend on available budget. Sites on both development and protection fields should be included, and ideally sites on more than one protection field, so that natural variation in geothermal ecosystems among protection fields can be quantified. This will also facilitate comparison with development fields so that within-site trends at development fields can be placed in a broader context. Issues of study design are best considered within the context of the available budget, which will dictate how much can be done.

12.6 Implementation

We envisage data collection by a combination of observations made on foot and from unmanned aerial vehicles (UAVs). For dangerous sites, a drone is best suited to making observations. Drones have been successfully deployed in vegetation monitoring activities in several contexts globally, for example in a study of cliff vegetation that combined horizontal images with Orthomosaic software to map a cliff system as part of threatened plant monitoring (Strumia *et al.* 2020). A similar approach could be employed to capture data from sites too dangerous to access on foot. This approach could be well suited to geothermal ecosystems, in which areas of high levels of surface activity are generally characterised by exposed bare soil and short vegetation. UAVs have been used to study geothermal habitats within the Taupō Volcanic Zone (Nishar *et al.* 2017). The possibility of using drone-based photogrammetry to build point clouds that model vegetation (e.g., Lane Scher *et al.* 2019) within plots by estimating species cover abundance within different height tiers should be investigated.

Once images of plots in hazardous areas have been captured, data collection could be completed remotely. Drones could take images of all plot locations that have been measured, the resulting images forming part of the permanent measurement record. Drones have already been used to capture orthorectified images at a site level for detailed vegetation mapping of geothermal ecosystems (Beadel *et al.* 2018). Some of the plots with established scrub and shrubland canopies could be measured by drone, and on foot, to compare the data obtained by each method from habitats with taller vegetation.

12.7 Habitat types

A final consideration of options applies to the measurement of different geothermal habitat types, and whether different plot methods should be applied to some or all of these. These habitat types are acid rain systems, geothermal streamsides, heated ground, hydrothermally altered ground, fumaroles and geothermal wetlands. With the exception of geothermal streamsides and geothermal wetlands, all could be sampled using plot-based methods. Geothermal streamsides comprise narrow bands of linear habitat that may need to be targeted for inclusion within a plot-based network. Acid rain systems would be difficult to quantify in a study without detailed information on steam chemistry. Fumaroles are very localised and sometimes temporary. Heated ground and hydrothermally altered ground habitat types all can be sampled by the same plot-based method (preferably grid based), including measurement of height frequency.

Geothermal wetlands present a different habitat type. These could be treated as wetlands and measured following the protocols recommended by Bellingham *et al.* (2021), or they could be treated as an extension of geothermal vegetation and measured by the protocols we suggest below. Both approaches could be tested to establish whether there are any particular advantages to one or the other. Drone-based photogrammetry may prove particularly valuable for measuring wetland vegetation.

13 Cost-benefit analysis

Factors affecting the cost of monitoring at geothermal sites include:

- The need for two staff to be present at all times for safety
- Geothermal induction courses that may need to be undertaken on development fields.
- The ability to access sites (land ownership) and time to gain permission/permits
- Size of sites and accessibility of sites
- Change within sites resulting in new plots needing to be established relatively frequently at some sites, or changes to the way in which a site is accessed resulting in more time in the field.
- Sampling intensity
- Write up of results, including statistical analysis.

The current (2023) inventory approach allows a large number of sites to be assessed for a relatively low cost (averaging around $6,500 per site, recognising that site size is very variable). Typical costs of resource consent monitoring, where transect monitoring and photopoints are undertaken, are in the region of $8-12,000 per transect[1].

An increase in plot number, transect number or inclusion of animal monitoring, will all result in additional monitoring cost.

Use of a drone is unlikely to be considerably cheaper than current monitoring, although it will have other benefits such as sampling of dangerous or sensitive sites.

Providing replication and random plot points mean that the costs of plot establishment in the initial phases are greater than later re-measurement. This is due to the microsite conditions that need to be taken account of, especially around site safety, which mean that some random points may not be practical.

Essentially there are five trade-offs associated with any monitoring protocol: plot size, replication, data intensity, sampling impact, and cost. The trade-off for plot size and replication is that as plot size increases it requires more resourcing to replicate plots. Another element to this trade-off is that as plot size decreases, more plots are needed to capture a representative sample of vegetation. Plot size and cost also trade-off, in that as plot sizes increase so too does sampling effort and cost. Data intensity and sampling impact also trade-off, i.e., the more aspects of vegetation structure and composition that are sampled, the higher the sampling impact. Data intensity and cost also trade-off; the more aspects of vegetation structure and composition that are sampled, the higher the sampling effort and cost (Table 5). Each of the protocols proposed by Bellingham *et al.* (2021) has strengths and weaknesses in different geothermal habitats which interact with these trade-offs, which are summarised in Table 6.

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[1] Costs in 2022

Table 5 Pros and cons associated with different sampling strategies, and the unit of replication (plots) through which data collection occurs.

		Pros	Cons
Sampling strategy	Random	Sample site selection is statistically robust	Rare vegetation types may be missed
			Inter-plot travel distances are maximised, especially if measurement sequence is also randomised.
	Stratified random	Sample site selection is statistically robust	Vegetation boundaries may move through time as geothermal activity centres move.
			Vegetation types may change through time. Plots remain fixed. This is an advantage of having fixed plots, but possibly a disadvantage of a stratified random strategy originally based on vegetation types that subsequently change in area and distribution through time.
	Regular	Sample site selection is statistically robust, given sufficient sample size	Rare vegetation types may be missed
		Inter-plot travel distances can be minimised	Impacts may be more concentrated
Plot shape	Square	Easier to conceptualise cover abundance within a square area, and to delineate plot boundary	Four control points, possible boundary relocation error in larger plot sizes
	Circular	one control point, lower relocation error	More challenging to conceptualise cover abundance within a circular area, and to delineate perimeter
			Reliance on a single control point for plot relocation unless additional points are established on the perimeter.
Plot size	Large	More comprehensive data	Slower
		Lower cost per area sampled	Less capacity to replicate within sites
			More trampling damage on site
	Small	Faster	More likely to miss sparsely-distributed biodiversity
		Can more easily replicate within sites	Higher cost per area sampled

Table 6 Pros and cons associated with methods recommended by Bellingham *et al.* (2021) as they might be applied in different geothermal environments (excluding acid rain systems and fumaroles)

Plot Method (from Bellingham et al. (2021)	Heated Ground		Geothermal Wetlands		Cooled Hydrothermally Altered Soils		Steamy Habitats	
	Pros	**Cons**	**Pros**	**Cons**	**Pros**	**Cons**	**Pros**	**Cons**
Forest	Comprehensive data	Challenging to establish in scrubby habitats.		Implementation in wetlands impractical	Comprehensive data	Time intensive		Plot size may be larger than scale of manifestation of this habitat type.
		Time intensive		Foot traffic intensive		Foot traffic intensive		Time intensive
		Foot traffic intensive						Foot traffic intensive
Wetland	Clear sampling strategy	Challenging to establish	Standard method.	Some vegetation types narrower than 5 m	Clear sampling strategy	Potentially foot traffic intensive	Clear sampling strategy	Plot size may be larger than scale of manifestation of this habitat type
		Potentially foot traffic intensive	Plot size scales with vegetation stature	Potentially foot traffic intensive	Plot size scales with vegetation stature			
		Vegetation boundaries may change through time, which may reduce representativeness of the sample,	Clear sampling strategy		Reverts to forest method in tall woody vegetation			
Perpetual herbaceous communities	Suited to low stature vegetation	Potentially foot traffic intensive		Potentially foot traffic intensive		Small plot size		Plot size more suited to scale of manifestation
	Not time intensive					Many plots required to achieve representative sample		

Plot Method (from Bellingham et al. (2021)	Heated Ground		Geothermal Wetlands		Cooled Hydrothermally Altered Soils		Steamy Habitats	
	Pros	Cons	Pros	Cons	Pros	Cons	Pros	Cons
Herbaceous communities on stable ground undergoing succession	Plot size scales with vegetation stature	Challenging to establish in some situations		Foot traffic intensive	Comprehensive data	Time intensive	Foot traffic intensive	Plot size may be larger than scale of manifestation of this habitat type
	Not time intensive	Time intensive				Foot traffic intensive		Time intensive
		Foot traffic intensive						Foot traffic intensive
Skeletal ecosystems on stable substrates	Plot size scales with vegetation stature	Challenging to establish in some contexts		Foot traffic intensive	Plot size scales with vegetation stature	Challenging to establish in some contexts	Foot traffic intensive	Plot size may be larger than scale of manifestation of this habitat type
	Not time intensive	Foot traffic intensive				Foot traffic intensive		
Skeletal soils on mobile substrates	Representative sampling at site level	High level of replication required	Representative sampling at site level	High level of replication required	Representative sampling at site level	High level of replication required	Representative sampling at site level	High level of replication required
	Clear sampling strategy		Clear sampling strategy	Small plot size	Clear sampling strategy	Small plot size	Clear sampling strategy	Small plot size
	Not time intensive		Not time intensive		Not time intensive		Not time intensive	
Proposed Geothermal ecosystems protocol	Comprehensive data	High level of replication required	Comprehensive data		Comprehensive data	Time intensive	Established method	Habitat may not scale to plot size appropriate for vegetation stature
	Flexible		Flexible				Flexible	

14 Recommendations

Indigenous dominance was the focus of the Bellingham *et al.* (2021) quantitative measure of ecological integrity. Bellingham *et al.* (2021) stress, however, that their focus specifically excludes other measures of ecosystem integrity such as ecosystem extent. Ecosystem extent and other metrics involving a range of ecosystem integrity indicators are included in the current monitoring of geothermal ecosystems conducted by Waikato Regional Council. As these are critical components of ecological integrity, their measurement should continue.

There is also established monitoring in development systems in relation to monitoring conditions attached to resource consents. There is value in continuing this monitoring, as it provides detailed, often spatially explicit, accounts of vegetation change through time. However, there is also scope to align this monitoring more closely to a national framework, thus achieving multiple goals. Monitoring as a function of consent conditions is not undertaken in a co-ordinated way, varying slightly among sites. We suggest that additional protocols be attached to these established monitoring programs, to capture the quantitative assessment of indigenous dominance advocated by Bellingham *et al.* (2021), in a manner compatible with the national Biodiversity Monitoring Framework. In addition, there are entire geothermal systems which currently have little if any formal monitoring, e.g., protected systems. Monitoring should be implemented at these sites to complete the national framework and provide a context for evaluation of development systems. Such monitoring will also provide valuable information on natural variation in systems without energy extraction, something which is currently lacking in existing monitoring.

Some additional protocols to be added to current monitoring to increase compatibility with the Biodiversity Monitoring and Reporting System are suggested below. These can be added to geothermal ecosystem monitoring already conducted by Waikato Regional Council.

Fauna monitoring could be incorporated easily into existing monitoring, following the Bellingham *et al.* (2021) methods. Bird count data will likely reflect wider landscape patterns, rather than relate specifically to geothermal habitat. Invertebrate monitoring was not part of the monitoring framework we were asked to consider.

Where new vegetation monitoring is required, the monitoring methods we suggest are dictated by geothermal habitat type. For geothermal wetlands we recommend using the protocols established for wetlands, which are well established throughout New Zealand and recommended by Bellingham *et al.* (2021), if and where these are possible to implement without extensive damage to sensitive vegetation, or harm to persons undertaking the monitoring.

For terrestrial geothermal vegetation, we recommend the use of plots whose size scales with vegetation stature. The following plot sizes are recommended for terrestrial geothermal habitats:

Forest, tall (>2 m) scrub, and shrubland: 10 x 10 m.
Short (<2 m) scrub and shrubland: 2 x 2 m.
Mossfield and lichenfield: 1 x 1 m.
Raw soil field 1 x 1 m

We recommend these plots be located in a stratified random manner, with the overall site being subdivided by habitat and vegetation type. The basis for this subdivision could be a standard vegetation classification system, such as that proposed by Clarkson *et al.* (2004) for wetland habitats, or an aggregation of vegetation and habitat types mapped as part of geothermal inventory surveys (Wildland Consultants 2014, 2020). For dangerous sites, we recommend overflying a drone to capture high resolution imagery, with plots located onto and measured from the orthorectified images that result. The plot sizes should follow the vegetation stature, as recommended for plot sizes above. Data on species cover abundance should be obtained from images.

A comparison of data capture from aerial images and ground-based measurement should be undertaken for a selection of plots measured using both methods, to assess the impact of vegetation stature on the quality of data gathered from aerial images.

Soil temperature measurements should be made strategically within plots.

Because of the extreme variability in geothermal sites, safety issues and inherent fragility, it is likely that the level of sampling, including replication, and sampling strategy will need to be tailored on a site-by-site basis. A study of the rate of recovery of geothermal vegetation types following disturbances associated with plot-measurement, or simulated disturbance regimes, should be undertaken to establish the minimum return time for plot remeasurement.

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Appendix 1: Summary of geothermal ecosystem monitoring methods from 51 publications in the Waikato Region describing monitoring or scientific study of geothermal ecosystems. Methods descriptions are quoted from the original text.

PART A

Report Reference	Year	Geothermal Field	Site Area Measurement	Geophysical Measurements	Vegetation Methods [except plots]	Vegetation Methods [plots]	RECCE Methods	Photopoints
Given D.R. 1978. Vegetation on heated soils at Karapiti, Wairakei. *Unpublished Report. Botany Division, DSIR, Christchurch*	1978	Wairakei						
Given D.R. 1980: Vegetation on heated soils at Karapiti, central North Island, New Zealand, and its relation to ground. New Zealand Journal of Botany 18: 1-13.	1980	Wairakei	A detailed vegetation survey was undertaken in February 1978 with the mapping carried out at a scale of 1:2500.	At regular (usually 25 cm) intervals along the transections, ground temperatures were measured at 25 mm intervals vertically from the surface to 150 mm depth using maximum-reading mercury thermometers.	Vegetation cover and ground temperature profiles were determined along transects of various lengths	Several 3 m square plots have been bared of vegetation to allow rates of colonisation to be estimated.		A series of photopoints has been established to assist in monitoring long-term changes.
Miller E.M. and Ecroyd C.E. 1993: Waikite Thermal Reserve: Vegetation, plant species, and special botanical features. *Report prepared for the Parks and Reserves Department of the Rotorua District Council.*	1993	Waikite		descriptive	descriptive			
Burns B.R. and Leathwick J. R. 1995: Geothermal vegetation dynamics in Te Kopia Scenic Reserve. *Science for Conservation 18*. Department of Conservation. Wellington. 26 pp.	1995	Te Kopia		At each plot, the following environmental and site data were collected: soil temperature at 0, 5, 10, and 15 cm depths, altitude, slope, canopy height, groundcover, and topographic position. Soil temperature was measured with a Digitron portable thermometer (model 3200KC) fitted with a 25 cm "bitumen" probe (model S016K)		Study area boundaries were chosen to include all geothermal vegetation using enlargements of the most recent (1991) colour aerial photos (scale = 1: 3300). Parallel E-W transects were systematically located over this study area every 200 m, and the vegetation composition and structure described on plots spaced every 50-100 m along these transects, giving a total of 56 plots. At each plot, vegetative cover by tier was recorded for all vascular plants and bryophytes in quadrats varying between 9 and 25 m2 in area. Small samples of plants (particularly bryophytes) were sometimes taken for verifying identification. At each plot, environmental and site data were collected, and at every second plot a soil sample was taken for later analysis		
Burns B.R., Whaley K.J., and Whaley P.T. 1995: Thermotolerant vegetation of the Tauhara Geothermal Field. *Landcare Research Contract Report: LC9596/020.*	1995	Tauhara		Variations in soil temperature at 10 cm depth were established by sampling with a Digitron portable thermometer (model 3200KC) fitted with a 25 cm 'bitumen' probe (model S016K).	We recorded all vascular and non-vascular plant species encountered on geothermally-influenced areas and described vegetation structure.			
Burns B.R., Whaley K.J., and Whaley P.T. 1996: Establishment of monitoring grids within geothermal vegetation, Wairakei Geothermal Field. *Landcare Research Contract Report: LC9596/135.*	1996	Wairakei	Aerial photographs covering the Wairakei Geothermal Field were obtained for the years 1945 and 1993. The colour and texture of current geothermal vegetation were used to interpret the extent of geothermal vegetation present in 1945. Vegetation extent at the two dates was compared by map overlay.	Soil temperatures at 10 cm depth were recorded at each 1m intersection along the grid. Soil temperatures were measured using a Digitron portable thermometer (model 3200KC) fitted with a 25 cm 'bitumen' probe (model S016K).	Seven baseline monitoring grids were established in geothermal vegetation at four sites (two at Alum Lake, two at Karapiti, two at Wairakei Thermal Valley, and one at Te Rautehuia) within the Wairakei Geothermal Field (Fig 1). Methodology largely followed that used by Burns (1996) at Te Kopia geothermal field. Each grid was located in vegetation relatively homogeneous in composition and structure. At three sites, two grids were installed to sample obviously different vegetation types. Grids were mostly 4 m x 19 m, providing 100 points 1 m apart in all directions. One grid (K2) had dimensions of 3 m x 24 m to improve the local homogeneity of the sample. Each grid was marked out with tagged wooden stakes placed 1 m apart in rows, each row located at 4 m intervals along the length of the grid. Vegetation composition and height was	35 permanent 20 cm x 20 cm quadrats along 2 transects (23 and 12 m in length) were established at Karapiti in July 1988 (and remeasured in July 1989) by Prof. J. Glime /Michigan Technological University, U.S.A.), Prof. Z. Iwatsuki (Hattori Botanical Laboratory, Japan), and Dr J. Beever (research associate, Landcare Research, Auckland). The longer transect was located in a community dominated by prostrate kānuka (*Kunzea ericoides* var. *microflora*) and the moss *Campylopus holomitrium*, and the shorter on an area covered by ash from a hydrothermal eruption in 1988. These transects were remeasured, with Dr Beever's assistance, in February 1996. At establishment, each quadrat was located at random within each metre of both transects, with one quadrat edge on the transect line. Quadrat positions were marked with wire pegs pushed into the ground. Within		

Report Reference	Year	Geothermal Field	Site Area Measurement	Geophysical Measurements	Vegetation Methods [except plots]	Vegetation Methods [plots]	RECCE Methods	Photopoints
					measured at each 1 m intersection along the grid. Measurement of approximately 100 points is recommended by Scott (1965) and Dickinson et al. (1992), and this determined the final grid size. Vegetation was sampled using a modified Scott height frequency pole constructed for a similar monitoring project in the Te Kopia geothermal field (Scott 1965, Burns 1996). The pole is 2.5 m long and marked at 10 cm intervals. Four wire rings attached to the pole delineate a circular sampling column of 5 cm diameter. We lowered the pole through the vegetation at each point and recorded the presence by species of foliage which intersected each 10 cm subsection of the column. A small spirit level attached to the back of the pole ensure that it was held vertically.	each quadrat in 1988, 1989, and 1996, the percentage cover of all vascular and non-vascular plant species, percentage litter cover, and percentage bare soil, surface soil temperature, surface moss temperature and soil temperature at 15 cm depth were recorded. Methods are similar to Glime and Iwatsuki (1994)		
Burns B.R. 1997b: Vegetation change along a geothermal stress gradient at the Te Kopia steamfield. *Journal of the Royal Society of New Zealand 2*: 279-294.	1997	Te Kopia		At each plot the following environmental and site data were collected: soil temperature at 0, 5, 10, and 15 cm depths, altitude, slope, canopy height, groundcover, and topographic position. Soil temperature was measured at the centre of the plot with a 'Digitron' portable thermometer (model 3200KC) fitted with a 25 cm 'bitumen' probe (model S016K). At approximately every second plot a soil sample was taken (22 plots). Soil temperature was measured at the centre of the plot with a 'Digitron' portable thermometer (model 3200KC) fitted with a 25 cm 'bitumen' probe (model S016K). Groundcover was recorded by percentage in five categories: bryophytes, vascular plants, rocks, bare soil, and litter. Topographic position was described using the nine-unit land surface model of Conacher & Dalrymple (1977). Each soil sample collected consisted of at least 20 soil plugs of 1.5 cm diameter to 10 cm depth extracted using a Hoffer tube and aggregated. Samples were initially analysed for pH (in H2O), conductivity, % soluble salts, CaCl2-extractable Al, water-soluble SO4, and DPTA-extractable Fe, Mn, Zn, and Cu (Blakemore et al. 1987; Hoyt & Nyborg 1972; Lindsay & Norvell 1978).	Areas of Te Kopia Scenic Reserve with geothermally influenced scrub vegetation were interpreted from the most recent aerial photos (Burns & Leathwick 1995). Parallel transects trending east to west were systematically located 200 m apart over these areas, and vegetation composition and structure were described on 48 plots regularly spaced at 100 m intervals along these transects in March 1993. Plot location was minimally adjusted where necessary to ensure plots occurred in homogeneous areas. Transects were considered complete when the soil temperature measured on a plot was at ambient levels (approximately 16°C in March: Dawson & Fisher 1964) and remained constant or decreased with depth.			
Merrett M.F. and Burns B. 1997: Biological assessment of the Rotokawa Geothermal Field. *Landcare Research Contract Report: LC 9798/019*.	1997	Rotokawa			emphasis on qualitative description			
Merrett M.F. and Burns B.R. 1998a: Thermotolerant vegetation of the Ohaaki Geothermal Field. *Landcare Research Contract Report: LC9798/084*.	1998	Ohaaki	Aerial photographs covering the Wairakei Geothermal Field were obtained for the years 1941, 1984 and 1997. The colour and texture of current geothermal vegetation were used to interpret the extent of geothermal vegetation present in 1941 and 1984 relative to static landscape features, e.g., rock outcrops, roads, and sinter terraces. This information was then used to assess changes over different time intervals.	Soil temperatures were measured at 15 cm depth using a Digitron portable thermometer fitted with a 25 cm 'bitumen' probe.	At each site, all vascular and non-vascular plant species encountered were recorded and vegetation structure noted.			

Report Reference	Year	Geothermal Field	Site Area Measurement	Geophysical Measurements	Vegetation Methods [except plots]	Vegetation Methods [plots]	RECCE Methods	Photopoints
Merrett M.F. and Burns B.R. 1998c: Wairakei Geothermal Field vegetation monitoring: changes after two years. *Landcare Research Contract Report: LC9798/089*.	1998	Wairakei			Grids were mostly 4 m x 19 m, providing 100 sampling points 1 m apart in all directions. On grid (Karapiti 2) had dimensions of 3 m x 24 m to improve the local homogeneity of the samples. Each grid was marked out with tagged wooden stakes placed 1 m apart in rows, each row located at 4 m intervals along the length of the grid. Vegetation composition and height, and soil temperatures at 10 cm depth were recorded at each 1 m intersection along the grid. Vegetation was sampled using a modified Scott height frequency pole, 2.5 m long and marked at 10 cm intervals (Scott 1965; Burns et al. 1996). Four wire rings attached to the pole delineate a circular sampling column of 5 cm diameter. We lowered the pole through the vegetation at each point and recorded the presence by species of foliage which intersected each 10 cm subsection of the column. A small spirit level attached to the back of the pole ensured that the pole was held vertically.			
Merrett M.F. and Clarkson B.R. 1999: Definition, description and illustrations of geothermally influenced terrestrial and emergent wetland vegetation. *Landcare Research Contract Report: LC9900/022.*	1999	Waikato Region			Qualitative description, with key to vegetation types.			
Wildland Consultants 2000: Geothermal vegetation of the Waikato Region. *Wildland Consultants Ltd Contract Report No. 297*. 178 pp.	2000	Waikato Region	Geothermal vegetation types were described for each site, and the extent of each type was mapped onto enlarged photocopies of aerial photographs. Vegetation type boundaries for each site were digitised in ArcView (v.3.1)		Geothermal vegetation types were described for each site			
Merrett M.F., Burns B.R., and Fitzgerald N.B. 2003: Reassessment of geothermal vegetation at Ohaaki Geothermal Field and establishment of monitoring transects. *Landcare Research Contract Report: LC0304/014*.	2003	Ohaaki		Soil temperatures were measured at 10 cm depth using a portable soil thermometer fitted with a 25 cm probe.	Four permanent monitoring transects were established in areas of geothermal vegetation. Each 1-m-wide transect was located in vegetation dominated by prostrate kānuka, and the corners marked with small (50 cm in height) wooden states each with a numbered aluminium tag attached. Vegetation composition and abundance (% cover), prostrate kānuka height, and soil temperatures were recorded along each transect at 1m intervals. Location of each transect recorded using a GPS unit. At each plot, foliage cover by height tier was recorded for all vascular plants and bryophytes in quadrats varying in area between 9 m2 (low vegetation) and 25 m2 (tall vegetation). Cover classes and tier heights followed those recommended in Allen (1992).			Eight photopoints were established at sites of geothermal activity and marked with a wooden stake. Photographs were taken of each transect and the eight photopoints. Locations of each photopoint recorded using a GPS unit.
Wildland Consultants 2003: Geothermal vegetation of the Waikato Region - Revised and expanded 2003. *Wildland Consultants Ltd Contract Report No.*	2003	Waikato Region	Geothermal vegetation types were described for each site, and the extent of each type was mapped onto enlarged photocopies of aerial photographs. Vegetation		Geothermal vegetation types were described for each site			

Report Reference	Year	Geothermal Field	Site Area Measurement	Geophysical Measurements	Vegetation Methods [except plots]	Vegetation Methods [plots]	RECCE Methods	Photopoints
664. Prepared for Environment Waikato. 225 pp.			type boundaries for each site were digitised in ArcView (v.3.1)					
Merrett M.F. and Fitzgerald N.B 2004: Changes in geothermally influenced vegetation at Mokai Geothermal Field 5 years after the start of geothermal energy extraction. *Landcare Research Contract Report: LC0304/084*. 34 pp.	2004	Mokai	interpretation of aerial photographs (without quantification)		Emphasis on qualitative description			
Wildland Consultants 2004c: Geothermal Vegetation of the Waikato Region - Revised 2004. *Wildland Consultants Ltd Contract Report No. 896*. Prepared for Environment Waikato. 244 pp.	2004	Waikato Region	Vegetation type boundaries for each site were digitised in ArcView (v.3.1)		Geothermal vegetation types were described for each site, and the extent of each type was mapped onto colour printouts of digital aerial photographs			
Merrett M. and Fitzgerald N. 2006. Thermotolerant vegetation of the Tauhara Geothermal Field. *Landcare Research Contract Report LC0506/118*. Prepared for Contact Energy. Landcare Research, Hamilton. 28 pp.	2006	Tauhara	Areas of thermotolerant vegetation were mapped using GPS and aerial photographs. The distribution of thermotolerant vegetation was compared with descriptions from earlier surveys.	Soil temperatures at 10 cm depth were measured.	In each area vegetation composition and structure were described.			Twelve photopoints were established and GPS coordinates were recorded. In prostrate kānuka vegetation fibreglass rods were used as markers
Wildland Consultants 2006: Field evaluations of five geothermal sites, Waikato Region, June 2006. *Wildland Consultants Ltd Contract Report No. 1403*. Prepared for Environment Waikato. 28 pp.	2006		field inspections were undertaken of five selected geothermal sites. These field inspections were to review site boundaries presented in the 2004 study of all the geothermal sites in the region.					
Bycroft C.M. and Beadel S.M. 2007: Distribution and density of *Christella* sp. 'thermal' *Cyclosorus interruptus*, and *Hypolepis dicksonioides*, at geothermal sites in the Waikato Region. *Wildland Consultants Ltd Contract Report No. 1611*.	2007	Waikato Region						
Wildland Consultants 2007: Requirements for the protection and enhancement of 'Craters of the Moon' - a geothermal natural area and tourist attraction near Taupō. *Wildland Consultants Ltd Contract Report No. 1785*. Prepared for Department of Conservation. 40 pp.	2007				A walk-through inspection of the reserve was undertaken on 29 August 2007.			
Wildland Consultants 2007a: Evaluation and mapping of selected geothermal sites for minor variation to Waikato Regional Plan - Geothermal vegetation and geophysical properties: February 2007. *Wildland Consultants Ltd Contract Report No. 1588*. Prepared for Environment Waikato. 57 pp.	2007	Waikato Region		The geophysical properties of the Tirohanga Road, Upper Atiamuri West and several sites around Tokaanu were identified as part of this project by Manfred Hochstein (Auckland Uniservices Ltd). Additional field equipment (Raytek IR gun, Fluke thermocouple meter plus probes, and standard thermometers) was supplied by IGNS Wairakei (courtesy of Mr C. Bromley). This equipment was checked for accuracy and calibrated at IGNS Wairakei on 2 February 2007.	Briefly, field surveys of nine sites were undertaken. A walk-through inspection of geothermal habitat was undertaken of all of the sites (where it was safe to do so). Vegetation type maps and description have been completed or updated and expanded for these sites. General information was also collected on threats, modification and vulnerability of each site. An additional five sites on private land where permission for access was not requested or granted at this stage (as per project brief) were viewed from the road. A vegetation assessment of these sites was undertaken based on what was seen from the road and using our best judgement of vegetation assessment from aerial photography.			

Report Reference	Year	Geothermal Field	Site Area Measurement	Geophysical Measurements	Vegetation Methods [except plots]	Vegetation Methods [plots]	RECCE Methods	Photopoints
Wildland Consultants 2007b: Field evaluations of nine geothermal sites, Waikato Region, June 2007. *Wildland Consultants Ltd Contract Report No. 1619.* Prepared for Environment Waikato. 56 pp.	2007	Waikato Region	Vegetation type boundaries for each site were digitised in ArcView (v.3.1)		A walk-through inspection of geothermal habitat was undertaken of all of three sites and parts of six sites. Geothermal vegetation types were described for each site, and the extent of each type was mapped onto colour printouts of digital aerial photographs			
Wildland Consultants 2007c: Requirements for the protection and enhancement of Broadlands Road Scenic Reserve. *Wildland Consultants Ltd Contract Report No. 1789.* Prepared for Department of Conservation. 37 pp.	2007	Tauhara			A walk-through inspection of the sites was undertaken on 29 August 2007.			
Mitchell Partnerships 2009: Ngatamariki Ecological Report. Prepared for Rotokawa Joint Venture Ltd.	2009	Ngatamariki						
Smale, MC, Fitzgerald, NB, Mason, NWH, Cave, SA 2009. Wairakei Geothermal field vegetation monitoring: Changes between 1995 and 2008. Landcare Research Contract Report: LC0809/116	2009	Wairakei		Soil temperature was measured using a portable digital thermometer fitted with a 20 cm ‘bitumen’ probe (K type thermocouple), which was inserted 10 cm into the soil. At some points the probe could not be inserted adequately due to the density of the substrate (e.g., rocks, tree stumps), so these points were excluded from the temperature data. Soil temperature data from 1997 was not included in this report due to uncertainties surrounding the method and accuracy of these measurements.	Each monitoring grid consists of 100 sampling points distributed 1 m apart. Six of the grids are 4 m x 19 m; one (Karapiti 1) has dimensions of 3 m x 24 m to improve the local homogeneity of the sample. Vegetation composition, height, and soil temperature at 10 cm depth were recorded at each 1 m intersection on the grid. Vegetation composition and height were measured using a modified Scott height frequency pole marked at 10 cm intervals. The pole was lowered vertically through the vegetation at each sampling point and the presence, by species, of foliage within a 5 cm diameter vertical column was recorded for each 10 cm interval. All vascular species were identified to species level; all mosses, liverworts, and lichens were grouped together as ‘other non-vascular’			
Wildland Consultants 2009: Establishment of Geothermal Vegetation Monitoring plots. Contract Report No. 2323. Prepared for GNS. 40 pp.	2009	Wairakei, Karapiti, Ashwood Park and Broadlands			Each plot is 5 m × 20 m and consists of a grid of sample points on a 1 m grid over the plot, resulting in 105 sample points per plot. To locate each sampling point a 20 m tape was laid out down each of the five longitudinal grid lines, maintaining the 1 m spacing between tapes their entire length. As far as possible, tapes were laid out parallel to the ground, and over the top of the vegetation. The sampling points were located directly and vertically below the 1 m tape intervals. Throughout the remainder of this document each 20 m tape is referred to as a transect. Sample points were located at 1 m intervals along each of the five transects, starting at 0 m. At each point, the presence of vegetation in height bands was recorded with the aid of a Scott height frequency pole (Scott 1965). This 2.5 m long pole was marked in 10 centimetre increments, to which a 5 cm diameter ring was attached. The pole was placed vertically over each sample point, and the presence/absence of plant species was recorded within the ring at each height band (i.e. within a 5 × 10 cm cylinder).		Cover abundance for the 20 x 5 m plot estimated	

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					For the Broadlands Road Reserve plot, and for some of the Ashwood Park plot (Line E), the cover abundance of each plant species (vascular and non-vascular) within each quadrat was estimated to the nearest 5%.			
Wildland Consultants 2009a: Orakei Korako Cave and Thermal Park - Interpretation and restoration. *Wildland Consultants Ltd Contract Report No. 2034*. 23 pp.	2009	Orakeikorako						
Wildland Consultants 2009c: Wilding pine control at Orakei Korako cave and thermal park. *Wildland Consultants Ltd Contract Report No. 2333*. Prepared for Wairakei Environmental Mitigation Charitable Trust. 12 pp.	2009	Orakeikorako			The following series of photographs provide a visual representation of the Orakei Korako Thermal Park pre and post wilding pine control works.			
Wildland Consultants 2011: Geothermal vegetation of the Waikato Region - An update based on 2007 aerial photographs. *Wildland Consultants Ltd Contract Report No. 2348*. Prepared for Waikato Regional Council. 515 pp.	2011	Waikato Region	Geothermal vegetation types were described for each site, and the extent of each type was mapped onto colour printouts of digital aerial photographs (2007) (scale *c.*1:5,000	Geophysical assessments have been undertaken for all or parts of 19 sites (listed in Table 1). Specific methods for these assessments varied slightly between the geophysical consultants, but generally the following methods were used. Locations for each feature were recorded using a GPS. Direct temperature measurements were made with a thermocouple on a 4 4 m long wire, or a 100 100 mm long rigid probe, connected to a Fluke multimeter. If the surface to be measured was not accessible, a Fluke IR thermometer was used, however this is subject to limitations, particularly if steam is present. The pH was measured with a Hanna Instruments pH meter with a maximum operating temperature of 50°C; if the spring temperature was > 50°C the water was cooled to less than 50°C before the pH measurement was taken or a pH paper strip was used.	Field survey of 37 sites was carried out between June 2010 and June 2011 using a survey team of two people for safety reasons. Sites were visited where there was the greatest expectation of change (e.g., new road construction in the vicinity of the site), if there were major changes indicated on 2007 aerial photographs, or if the site had not been inspected before. Geothermal vegetation types were described for each site, and the extent of each type was mapped onto colour printouts of digital aerial photographs (2007) (scale c.1:5,000). Field assessments addressed the following components: the extent and type of vegetation present; indigenous flora (including the presence of any threatened plants); fauna present (which included a literature review for each site); current condition; invasive exotic plants; human impacts; grazing; adjoining land use and management requirements.			
Wildland Consultants 2011a: Priorities for pest plant control, pest animal control, and fencing at geothermal sites in the Waikato Region in 2011. *Wildland Consultants Ltd Contract Report No. 2755*. Prepared for Waikato Regional Council.	2011	Waikato Region						
Wildland Consultants 2011b: Ranking of sites with geothermal vegetation and habitats for biodiversity management in the Waikato Region. Wildland Consultants Ltd Contract Report No. 2756. Prepared for Waikato Regional Council.	2011	Waikato Region						
van Manen SM, Reeves R. 2012: An Assessment of Changes in Kunzea ericoides var. microflora and Other Hydrothermal Vegetation at the Wairakei–Tauhara Geothermal Field, New Zealand. Environmental Management 50: 766-786.	2012	Wairakei-Tauhara	Aerial photographs of the Broadlands Road area were obtained from the Taupō District Council. Photographs were available from 1946, 1961, 1969, 1971, 1976, 1983, and 2007. The 1946 photograph showed the area before development of the Wairakei geothermal field. Aerial photographs of the	At each vegetation survey plot, 105 soil temperature measurements were obtained at 0.1 m (T0.1) depth. Temperature measurements at 1 m (T1) depth were obtained at 2 m intervals where possible; occasionally hard substrate precluded the thermocouple from reaching 1 m depth. Soil temperatures were recorded using a Yokogawa meter and a K-type thermistor. Soil samples were collected at the same locations that 1 m depth temperatures were obtained but at 2 m intervals. Soil pH was determined potentiometrically by Hill	Because two of the plots (Karapiti and Geyser Valley) had been previously sampled (Merrett and Burns 1998) using the Scott height-frequency method (Scott 1965), the same survey methodology was used. To make the results comparable across plots, the Scott height-frequency method was also applied to the two new plots (Ashwood Park and Broadlands Road Reserve). The Scott height-frequency			

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			Broadlands Road Reserve were georeferenced and analysed using ArcMAP (Esri, USA) software. To determine the areas covered by bare ground and *K. ericoides* var. *microflora*, polygons were drawn, and the areas covered by these were calculated and summed.	Laboratories (Hamilton, New Zealand) in a slurry system (1:2 volumetric ratio of soil to water) using an electronic pH meter. Because the T0.1, T1, pH, and maximum height of *K. ericoides* var. *microflora* (h) data were continuous but not normally distributed, Spearman rank order correlation coefficients as determined in SPSS (IBM,. USA) were used to determine if there were correlations between these variables.	method uses a 2.5 m long pole that is marked in 0.10 m increments and has a 0.05 m diameter ring attached. The pole is placed vertically over each sample point, and the presence or absence of plant species within the ring are recorded for each 0.1 m height band to obtain height-frequency data. Survey plots consisted of 5 transects spaced 1 m apart and of 20 m each in size. Data were collected directly vertically at 1 m intervals along each transect, resulting in 21 data points per line and 105 sampling points per plot. From the Scott-height pole data, a single summed height-frequency value [biomass index or above-ground biomass index (McIntosh and others 1983)] was derived for each species at each vegetation survey plot by summing the frequency in each height category. As is customary (e.g., Scott 1965; McIntosh and others 1983; Dickinson and others 1992), data have been displayed graphically (Figs. 4 through 6); for each height band (y-axis) the length of the bar in the x-direction is proportional to the biomass index value of the species represented. It should be noted that the graph displays vegetation composition and structure, not the shape of individual plants (Scott 1965).			
Wildland Consultants 2012: Geothermal vegetation of the Waikato Region - an update based on 2007 aerial photographs. Wildland Consultants Ltd Contract Report No. 2348. Prepared for Waikato Regional Council. 528 pp.	2012	Waikato Region	Geothermal vegetation types were described for each site, and the extent of each type was mapped onto colour printouts of digital aerial photographs (2007) (scale *c.*1:5,000)	Geophysical assessments have been undertaken for all or parts of 19 sites (listed in Table 1). Specific methods for these assessments varied slightly between the geophysical consultants, but generally the following methods were used. Locations for each feature were recorded using a GPS. Direct temperature measurements were made with a thermocouple on a 4 4 m long wire, or a 100 100 mm long rigid probe, connected to a Fluke multimeter. If the surface to be measured was not accessible, a Fluke IR thermometer was used, however this is subject to limitations, particularly if steam is present. The pH was measured with a Hanna Instruments pH meter with a maximum operating temperature of 50°C; if the spring temperature was > 50°C the water was cooled to less than 50°C before the pH measurement was taken or a pH paper strip was used. Further details are provided on each site sheet.	Field survey of 37 sites was carried out between June 2010 and June 2011 using a survey team of two people for safety reasons. Sites were visited where there was the greatest expectation of change (e.g., new road construction in the vicinity of the site), if there were major changes indicated on 2007 aerial photographs, or if the site had not been inspected before. Geothermal vegetation types were described for each site, and the extent of each type was mapped onto colour printouts of digital aerial photographs (2007) (scale c.1:5,000)			
Wildland Consultants 2013: Ecological monitoring of geothermal vegetation in the Wairakei geothermal field 2013. *Wildland Consultants Ltd Contract Report No. 3109*. Prepared for Contact Energy. 21 pp.	2013	Wairakei		Soil temperature was measured using a Center 300 portable digital 'K-Type" thermometer fitted with a 40 cm 'bitumen' probe inserted 10 cm into the soil.	The existing grids at each site were relocated (Figure 1). Six of the grids at Wairakei are 4 ´ 19 m, with one grid at 3 ´ 24 m. These monitoring grids were established at seven sites in 1995/96 and remeasured and photographed in 1997, 2002, and 2008. The methods and results for these previous monitoring rounds are described by Burns et al. (1996), Merrett and Burns (1998), and Smale et al. 2009. Monitoring at one of the sites, Te Rautehuia, ceased from 2008 as the site no longer supported geothermal vegetation. At each 1 m intersection within the grids the following parameters were measured and recorded, adhering to the previous			All monitoring grids were rephotographed according to previous methods

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					methods: · Vegetation composition and height using a modified Scott height frequency pole marked at 10 cm intervals, lowered vertically through the vegetation at each sampling point and the presence, by species, of foliage within a 5 cm vertical column recorded at each 10 cm interval. Vegetation height was calculated as the mid-point of the maximum height interval occupied. All vascular species were identified to species level, mosses, liverworts and lichens were grouped as 'non-vascular".			
Wildland Consultants 2013: Ecological assessment and ecological restoration advice, Otumuheke Stream, Taupō. *Wildland Consultants Ltd Contract Report No. 3082*. Prepared for Waikato Regional Council. 73 pp.	2013				A walk-through inspection of the site was undertaken on 13 December 2012. The vegetation and habitats present were mapped and described. Vascular plants present were listed.			0
Wildland Consultants 2014: Ranking of geothermal ecosystems for biodiversity management in the Waikato Region. Wildland Consultants Ltd Contract Report No. 2756a. Prepared for Waikato Regional Council. 19 pp	2014	Waikato Region						
Wildland Consultants 2014: Geothermal vegetation of the Waikato Region, 2014. Wildland Consultants Ltd Contract Report No. 3330. Prepared for Waikato Regional Council. 526 pp.	2014			In 2007 and 2010, geophysical assessments were undertaken for all or parts of 19 geothermal sites within the Waikato Region (see Table 1). Specific methods for these assessments varied slightly between the geophysical consultants, but generally the following methods were used: • Locations of each feature were recorded using a GPS. • Direct temperature measurements were made with a thermocouple on a 4 m long wire, or a 100 mm long rigid probe, connected to a Fluke multimeter. If the surface to be measured was not accessible, a Fluke infrared (IR) thermometer was used; however this has limited accuracy, particularly where steam blocks a clear view of the feature. • The pH was measured with a Hanna Instruments pH meter with a maximum operating temperature of 50 °C; if the spring temperature was >50 °C the water	Field survey of 25 sites was carried out between January and July 2014 using a survey team of two people for safety reasons. Geothermal vegetation types were described for each site, and the extent of each type was mapped onto colour printouts of digital aerial photographs (2012) (scale c.1:5,000). Field assessments addressed the following components: the extent and types of vegetation and habitats; indigenous flora and fauna (including threatened species); current condition of vegetation and habitats; invasive exotic plants; human impacts; grazing; adjoining land use, and management requirements.			
Wildland Consultants 2015: Application of ecological indicators for the extent, condition, and protection level of geothermal habitats, Waikato Region. Contract Report No. 3504a. Prepared for Waikato Regional Council. 22 pp.	2015	Waikato Region						
Wildland Consultants 2015: Ecological effects of proposed steamfield expansion at the Rotokawa geothermal field, Taupō. Contract Report No. 3623.	2015	Rotokawa	The vegetation maps prepared for Lake Rotokawa and Rotokawa North in 2017 (Wildland Consultants 2018) were digitally overlaid onto 2021 aerial photographs. Readily apparent changes to vegetation between 2017 and 2021 were identified and vegetation boundaries were updated in the field based on the 2021 aerial images. The mapping of Rotokawa North was limited	Soil temperature (°C) at 10 centimetres depth was recorded at one metre intervals along the side of the transect labelled with fibreglass pegs (origin line). Soil temperature at 40 centimetres depth was also recorded at a selection of these locations (two metres apart on 10 metre transects, and three metres apart on the 15 metre transect). Notes were made when the soil was too firm to allow temperature probes to be inserted at either of these depths.	Monitoring activities included transect and photopoint monitoring. The four transects established in 2002 and the two transects established in 2017 were relocated. Five of these transects were remeasured in 2021. Scott height frequency was measured at the transects established in 2017 at one metre intervals along each line marked with a tape measure. A modified 2.5 metre Scott height frequency pole (Scott 1965) was placed vertically at each sampling point. The presence or absence of vascular and non-vascular	Transects established in 2002 (Transects 1-4) Visual estimation of plant species cover occurred within contiguous 1 × 1 metre subplots along each transect. Subplots along each transect were placed between Line 1 and Line 2. Total percentage cover of vascular and non-vascular plant species was recorded in each plot. The maximum height of geothermal kānuka (and any other woody species) in each plot was recorded. Transects established in 2017 (Transects 5-6) Estimation of plant species cover occurred within contiguous 3 ×		Photographs were taken at all of the 22 established photopoints. Photopoint 7 was considered too unsafe to access in 2017, but a new track had been cut prior to the 2021 site visit, so this photopoint was rephotographed in 2021. Photopoint 5a was considered too unsafe to access in 2021. Photopoint locations, photographs and descriptions are presented in Volume 2, Attachments 2 and 3. Photographs taken in 2021 were compared with photographs taken in 2017, 2012 and 2002

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			to the extent of the 2017 and 2021 aerial photographs provided. Changes to the extent or types of vegetation and habitats between 2017 and 2021 were assessed and described.		species was recorded at 10 centimetre height intervals and within a 5 × 10 centimetre 'cylinder' (Scott 1965). Non-vascular species were only recorded if present in the 1-10 centimetre tier.	3 metre plots (placed between Line 0 and Line 3) along each transect. The total percentage cover of vascular and non-vascular plant species in <0.3 metre, 0.3 to 2 metre, and >2 metre vegetation tiers was estimated, along with the measurement and estimation of the following parameters: • Environmental variables: drainage (good, moderate, poor), slope (degrees), and aspect (degrees). • Percentage cover of bare ground, gravel, rock, sinter, open water, dead vegetation, live vegetation, leaf litter, and woody debris. • Height (metres) and species of tallest woody species present. The height of the tallest geothermal kānuka was also measured if it was not the tallest species. • Animal browse (plant species, animal species, degree)		(Fitzgerald et al. 2012) where applicable. In 2017 digital photographs were taken with a Canon EOS7D using either a Canon EF 24-105 mm f/4L IS USM lens or a Canon EFS 10-22 mm f/3.5-4.5 USM lens. In 2021 the photographs were taken with an iPhone XS Max. The focal length was based on the area shown in previous photographs or what was most appropriate for the photograph at the time. Each photopoint site was marked with a fibreglass peg or, if the vegetation was tall, a green plastic waratah. A photopoint record sheet was used to record GPS location, bearing, and distinctive physical features to enable the photopoints to be reassessed in the future even if markers are lost. Twelve additional site photographs that were taken were also fully described (Attachment 4 in Volume 2 of this report). These photographs were taken to ensure that at least 20 photopoints can be reassessed in the future given that safe access to all sites is not always possible in a dynamic geothermal environment.
Wildland Consultants 2016: Application of ecological indicators for the extent, condition, and protection level of geothermal habitats, Waikato Region. Wildland Consultants Ltd Contract Report No. 3504b. Prepared for Waikato Regional Council. 39 pp.	2016	Waikato Region						
Wildland Consultants 2016: Geothermal monitoring at Broadlands Road Reserve and Crown Road, Taupō, 2016. Wildland Consultants Ltd Contract Report No. 3109b. Prepared for Contact Energy. 40 pp.	2016	Tauhara		Soil temperatures (°C) at 10 cm depth were recorded at the same 1 m intervals along transects as the Scott height frequency sampling points. Soil temperatures were also collected during each sub-plot measurement; at the diagonally opposite corner to the Scott height temperature position.	Three plots are 22 m long and 4 m wide, the fourth (a remeasured plot established in 2009 at Broadlands Road Reserve, Plot BRD-A) is 20 m long and 4 m wide (Table 1). Five 20 m-long transects were measured at each plot. Transect 1 starts at Corner A. Wooden pegs were placed at each corner of the three longer plots to mark plot boundaries and each were labelled with a numbered metal tag. At BRD-A, the four wooden pegs occur at: Corner A (1 0), Corner D (5-0), on Transect 1 at 16 metres (1-16), and on Transect 5 at 11.7 metres (5-11.7). Sample points were established at 1 m intervals along each of the five transects in each plot (between 0 m and 20 m in Plot BRD-A, and between 1 m and 21 m in Plots BRD-B, AP A and CRD-A). Each sample point is numbered sequentially indicating transect line number and point site; for example, sample point 1-19 is on Transect 1 at 19 m. A modified 2.5 m Scott height frequency pole (Scott 1965) was placed vertically at each sampling point. The presence or absence of vascular and non-vascular species was recorded at 10 cm height intervals and within a 5 × 10 cm 'cylinder' (Scott 1965; Burns 1996).	Measurement of plant species cover occurred at five metre intervals along each transect. Sub-plots of 0.5 × 0.5 m were established between the 1 m mark and the 1.5 m mark, north of each transect (and then at the 6, 11, and 16 m marks in all plots). Sub-plots along Transect 5 were placed outside of plot boundaries. Subplots measured percentage cover of vascular and non-vascular plant species in four height tiers: 0-10 cm, 10-30 cm, 30-200 cm, and 200-500 cm.	A modified RECCE sheet (from Hurst and Allen 2007) was used to estimate the vegetation composition in each plot. Each 20 m or 22 m plot was divided into ten 2 × 4 m subplots, with the total cover of vegetation and ground cover variables being visually estimated within five height tiers (4: 2-5 m, 5: 0.3-2 m, 6: 0-0.3 m, 7: epiphytes, groundcover) in each subplot. The subplots in the 22 m length plots started at 1 m and finished at 21 m.	Photographs provide an up-to-date visual record of vegetation change over time. Photographs were taken at two existing photopoints and established at 15 new locations located in geothermally-active parts of both Crown Road (including Ashwood Park) and Broadlands Road Reserve (see Table 1 for grid references and Figure 1 - Appendix 1 - for locations). Each photopoint site has been marked with a wooden peg, a green plastic waratah, or a white photopoint marker as appropriate; Table 2 lists which style of marker was used at each site. An existing survey peg was used at Crown Road Photopoint 7. Digital photographs were taken with Canon EOS7D using either a Canon EF 24-105mm f/4L IS USM lens or a Canon EFS 10-22mm f/3.5-4.5 USM lens. The focal length was based on the area shown in previous photographs or what was most appropriate for the photograph at the time. Photographs taken in 2016 were compared with photographs taken in 2009 (Wildland Consultants 2009) or 2013 (Wildland Consultants 2013b) where applicable, or, fully

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					Plot BRD-A at Broadlands Road is 20 m long. Data collected from other geothermal sites suggests that corner posts influence the vegetation immediately adjacent to them (see Wildland Consultants 2014). Data was therefore also collected from the 0.5 and 19.5 m points. Although information was collected at 0 m and 20 m, the data was excluded from the soil temperature and vegetation analyses.			described if they were established during the current fieldwork. See Appendix 3 for photopoint photographs and their descriptions.
Wildland Consultants 2016: Ecological monitoring in Ngatamariki geothermal area, 2016. Volume 1. Contract Report No. 2883d. Prepared for Mercury New Zealand Ltd.	2016	Ngatamariki	Aerial photographs of the Ngatamariki Scenic Reserve and surrounds were taken on 31 August 2016 at a scale of 1:2,000, with a resolution of 0.212 metre pixel size. A Canon 5D Mk II full frame digital SLR camera was used, with a calibrated 28 mm lens. Orthorectified photographs have been produced by Agisoft. The vegetation and habitat type map prepared in 2015 on 2015 aerial photographs (Wildland Consultants 2015) was updated and refined on 2016 aerial photographs during the site visits in 2016. The boundaries and descriptions of the mapped vegetation types have been further appraised, and revised where necessary, during the current study (using 2016 aerial photography) to reflect any changes in plant species composition and extent. It should be noted that the resolution quality of the aerial photographs available has increased each year since 2012.	Soil temperatures were measured using a thermometer (accurate to 1%) at a depth of 0-10 cm, depending on the hardness of the substrate, at 1 m intervals along the four transects.	Four monitoring transects were established in 2012 according to the indicative locations provided by the Department of Conservation; with two transects at Ngatamariki North and two at Ngatamariki South. The transect locations were selected to represent the diversity of geothermal vegetation at Ngatamariki. Transects were not located randomly because areas of geothermal vegetation at Ngatamariki are relatively small and discontinuous, some geothermal areas are unsafe to work in, and some plant populations and features are vulnerable to trampling disturbance. The transect length varied at each site in order to capture a selection of the diversity of vegetation types present at Ngatamariki and are as follows: Transect A - 28 m, Transect B - 20 m, Transect C - 40 m, and Transect D - 50 m. Transect locations are shown in Figure 3 and transect details are presented in Appendix 1. Descriptions, and selected site photographs taken along the length of transects are presented in Volume 2; Attachment 1. Each transect is marked at either end using plastic green waratahs, between which a tape measure is placed that delineates the centre of each 1 m wide plot along the transect, and enables placement of quadrats at 1 m intervals (see Figure 1). At two transects (Transect C and Transect D), origin points (0 m) are marked with wooden posts as it was not possible to hammer plastic waratahs into the concrete-like sinter. Waratahs were also placed along the length of the transects to enable tape measures to© 2016 3 Contract Report No. 2883d - Volume 1 be placed accurately at future remeasurements. These waratahs can also be used to relocate transects if markers are removed or disturbed (e.g., by hydrothermal eruption). A numbered metal tag was wired to the top of each marker post to help with future identification. In 2012, GPS coordinates (NZTM) were taken at each waratah/wooden post. Photographs were also taken from most marker posts to help	The tape measure delineates the middle of the transect. A contiguous series of 1 × 1 m plots, centred on the tape, was measured at each metre mark along the transect line. In each 1 × 1 m plot, the percent cover of all vascular plant species present in the 2-5 m, 5-12 m, 12-25 m, and >25 m vegetation tiers1 was estimated and recorded. A 0.5 × 0.5 m quadrat was placed in the lower quadrant on the left-hand side of the tape of each 1 × 1 m plot (Figure 2). In the 0.5 × 0.5 m quadrat, the percent cover of all plant species present (vascular and non-vascular) was estimated and recorded in two vegetation tiers (<30 cm and 30 cm-2 m).		Ten permanent photopoint sites (five in Ngatamariki North and five in Ngatamariki South) were established in 2012 to monitor the range of vegetation and habitats present in the Ngatamariki Geothermal Area (locations are shown in Figure 3, and details are presented in Appendix 2). Each photopoint was permanently marked using a green plastic waratah. In 2012, a series of photographs was taken at eight of the ten photopoints and one photograph was taken at the remaining two photopoints; this resulted in a total of 56 photographs. The photograph series compiled in 2012 was retaken in 2013, 2014, and 2015, but only one photograph from each photopoint was chosen for inclusion within this report to measure visible change over time. Photographs used for comparison were chosen to show the full range of geothermal vegetation and habitats present within the site. For sites where a series of photographs was taken, the comparison photograph can be changed to another photograph from the series if, for instance, the view becomes obscured over time, or if a different photograph records interesting change that has occurred at the site between surveys. In 2016, all photographs were taken with a Canon EOS 7D camera with a Canon EF-S 10-22 f3.5-4.5 USM lens. These photographs were taken at a 35 mm equivalent of 27 mm. The original photographs are in RAW files, but have been converted into JPG files for long-term storage. Note: A few photographs presented in Volume 2 in 2014 were taken with an Olympus µ850 SW, 35 mm lens equivalent.

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					with placement of the tape measure at future remeasurements.			
Wildland Consultants 2016: Relationships between ground and aerial photography and geothermal vegetation at craters of the moon geothermal area, Waikato. Contract Report No. 4010.	2016	Atiamuri			Normalised Difference Vegetation Index. See report for description of methods			
Wildland Consultants 2017: Ecological monitoring of geothermal vegetation in the Ohaaki geothermal field 2017. Wildland Consultants Ltd Contract Report No. 3109e. Prepared for Contact Energy. 41 pp.	2017	Ohaaki		Temperature was measured using a Centre 300 portable digital "K-Type" thermometer fitted with a 40 cm 'bitumen' probe inserted into the soil. Measurements at approximately 10 cm deep were taken at one metre intervals along each transect and also at 40 cm deep every five metres along each transect (Appendix 1).	Transect 1 was not found and a new transect (Transect 5) was established to replace it in a nearby location. Two existing fibreglass pegs were found out of the ground at Transect 2 and 3, and used to realign the transect as closely to the original layout as possible. No existing markers were found at Transect 4, so the transect was re-established in an area that appeared to be similar to photographs of the original transect. In 2017, plastic green waratahs were erected in the corners of the transects to permanently mark the new transects. To avoid influencing vegetation within the transects, these waratahs were erected at a distance from the transects. In most cases this was one metre outside of the plot; see Appendix 1. Because the exact location of the existing transects could not be found it was not possible to make accurate comparisons of transects between years. Simple summaries of the data collected were made.	The maximum and average height of geothermal kānuka was recorded within 1 × 1 metre quadrats along the length of the transects. If the height of the tallest species in the transect was not geothermal kānuka, the species identity and height was also recorded. Percentage cover of each plant species and ground cover variables (e.g., litter, bare ground, rock) was estimated within 1 × 1 metre quadrants along the length of the transects.		Photopoints were relocated and photographs taken (Appendix 5). Markers were not found at any of the existing photopoints, so photopoints were taken at a similar location, representative of previous photographs.
Beadel S, Shaw W, Bawden R, Bycroft C, Wilcox F, McQueen J, Lloyd K. 2018: Sustainable management of geothermal vegetation in the Waikato Region, New Zealand, including application of ecological indicators and new monitoring technology trials. Geothermics 73: 91-99.	2018	Waikato Region						
Reeves RR, Wilke M, Cashmore P, Macdonald N, Thompson K. 2018: Physical and ecological effects of rehabilitating the geothermally influenced Waikite Wetland, New Zealand. Journal of Environmental Management 228: 279-291.	2018	Waikite		Depth to the water table were measured at 7 shallow (< 3 m depth) piezometer sites (WE-WL1 – WE-WL7) (Fig. 1) around the wetland. SiteWE-WL7 was installed in December 2015. Data were collected over two periods: From 18/09/2009 to 6/4/2011, and 14/1/2014 to 31/12/2016. Odyssey Z412 capacitive water level loggers were installed at each site logging every 10 min, with manual dip measurements obtained at the time of each data download. The automated data were corrected for drift. Gaps in logger data are caused by equipment malfunctions, off scale data, or when the data could not be corrected for drift. Water temperature data loggers recording hourly data were installed at six sites (WE1008, Inlet, Outlet, Stream-upgradient, Delta and WE-AIR (air temperature)) (Fig. 1). Gaps in logger data were caused by equipment malfunction or battery issues. Ground temperature measurements at 1 m depth were measured on 18/9/2009 and 10/2/2017 to assess shallow ground temperature changes associated with installing the weir and raising the water level	Geothermal fern monitoring was undertaken by DOC along sections of the Otamakokore Stream that runs through the wetland between 2010 and 2017. Repeat surveys were done once a year during the summer months between January and March. The stream was divided into 12 transects (Fig. 1), with the transects permanently marked to ensure repeatability between surveys. Transects 1 to 8 were monitored over the entire period, with transects 9-11 added in 2014 and transect 7a added in 2015. Measurements were taken on the true left and the true right bank of the stream. Three geothermal fern taxa were measured: *Christella* aff. *dentata* 'thermal' (Christella) (number of live fronds), Cyclosorus interruptus (*C. interruptus*) (number of live fronds) and *Nephrolepis flexuosa* (*N. flexuosa*) (coverage in m^2). In 2010, 2011 one small fern of *N. flexuosa* was recorded but coverage was not measured. Changes in the distribution of blackberry and the water surface of the			

Report Reference	Year	Geothermal Field	Site Area Measurement	Geophysical Measurements	Vegetation Methods [except plots]	Vegetation Methods [plots]	RECCE Methods	Photopoints
					wetland were made by comparing aerial photography collected in 2013 (LINZ, 2017), with orthophotography collected by unmanned aerial vehicles in 2015 (shortly after weir installation) and 2017			
Wildland Consultants 2019: Baseline monitoring at 39A2A (Umupokapoka) Lagoon, Kawerau -2019. Contract Report No. 5202a.	2019	Kawerau	A field map of Umupokapoka Lagoon (the project area) was prepared using aerial photographs (BOPLASS 2018/19) at a scale of 1:1,200. Vegetation and habitats within the project area were mapped onto a hard copy of the field map during field work. Vegetation and habitat types were described following the structural classes outlined by Atkinson (1985). The vegetation and habitat map was digitised using ArcGIS 10.6.	Soil temperature was measured at 0-10 centimetres depth and at 40 centimetres depth (where substrate was a suitable density) at twenty locations within each plot. The locations where soil temperature was measured are shown in Appendix 2		Eight permanent vegetation monitoring plots were established at the locations identified in the monitoring programme (4Sight Consulting 2017). Each plot was 10 ´ 10 metres and marked with a combination of fibreglass poles and white photopoint markers. Existing wooden markers for these plots were removed (where it was safe to do so) because based on previous experience, wooden posts may influence the growth of vegetation around them and do not last well in geothermal environments. Each plot was subdivided into four subplots (labelled A-D) and the following measurements were undertaken: · All vascular plant species within each subplot were identified and recorded. Nonvascular plant species were recorded to the nearest taxonomic level as possible in the field. · Plant cover - Within each subplot, the percent cover of each plant species was estimated in height tiers: 0-0.3 metres tall and 0.3-2 metres tall, 2-5 metres tall, and greater than five metres tall (all vegetation was less than 12 metres tall). Tiers followed a similar method to Hurst and Allen (2007). The cover of non-vascular plant species was recorded at genus level, where possible. Ground cover variables (such as leaf litter and bare ground) were recorded in the 0-0.3 metre height tier only (when they were present). · Geothermal kānuka density - Within each subplot, the number of geothermal kānuka present were counted, within height classes of 0-0.3 metres tall, 0.3-2 metres tall, 2-5 metres tall, and greater than five metres tall. For efficiency, when there were large numbers of plants in the 0-0.3 metre height tier, an approximate estimate of the number of plants was made. In Plots 3-8, the number of plants of each other woody plant species which were present in each height tier was also recorded (in Plot 4, this was only undertaken within Subplot A). In Plots 1 and 2, the number of plants of other plant species was not recorded. · Maximum height - Within each subplot, the height of the tallest individual of each woody plant species was recorded. The species was also recorded.		Twenty-five photopoints were established at Umupokapoka Lagoon during the field work. The location (NZTM), methods of permanent marking (where possible), and bearing (magnetic north) of each photopoint were recorded (see Table 2). A description of the vegetation at each photopoint was recorded onto photopoint sheets in the field. Photographs were taken at various focus lengths with either a Canon PowerShot D30 camera or iPhone XS Max.
Wildland Consultants 2019: Geothermal monitoring at Broadlands Road Reserve and Crown Road, Taupō, 2019. Contract Report No. 3109f. Prepared for Contact Energy. 73 pp.	2019	Tauhara	The broad vegetation and habitat types present in each plot were mapped in the field and then digitised as a scale-diagram using ArcGIS. Key features such as individual plants of geothermal kānuka were also mapped. The maps	Soil temperatures (°C) at 10 centimetre depth were recorded at the same 1 metre intervals along transects as the Scott height frequency sampling points. Soil temperatures were also collected during each sub-plot measurement; at the diagonally opposite corner to the Scott height temperature position		Measurement of plant species cover occurred at 5 metre intervals along each transect. Sub-plots of 0.5 × 0.5 metres were established between the 1 metre mark and the 1.5 metre mark, north of each transect (and then at the 6, 11, and 16 metre marks in all plots). Sub-plots along Transect 5 were placed outside of the plot boundary. Subplots measured	A modified RECCE sheet (from Hurst and Allen 2007) was used to estimate the vegetation composition in each plot. Each 20 metre or 22 metre long plot was divided into ten 2 × 4 metre subplots, with the total cover of vegetation and ground cover variables being visually estimated within five height tier classes (4: 2-5 metre, 5: 0.3-	Photographs provide an up-to-date visual record of vegetation change over time. Photographs were taken at seventeen existing photopoint locations in geothermally-active parts of both Crown Road (including Ashwood Park) and Broadlands Road Reserve (see Table 2 for details and Appendix 1 for locations). Four

Report Reference	Year	Geothermal Field	Site Area Measurement	Geophysical Measurements	Vegetation Methods [except plots]	Vegetation Methods [plots]	RECCE Methods	Photopoints
			provide a birds-eye-view of vegetation cover in each plot. The area of each vegetation and habitat type within each plot was calculated using ArcGIS. Plot vegetation maps were compared to those which were made for each plot in 2016 (Wildland Consultants 2016).			percentage cover of vascular and non-vascular plant species in four height tiers: 0-10 centimetres, 10-30 centimetres, 30-200 centimetres, and 200-500 centimetres.	2 metre, 6: 0-0.3 metre, 7: epiphytes and groundcover) in each subplot. The subplots in the 22 metre long plots started at 1 metre and finished at 21 metres	additional photopoints were established in 2019 (BR5E, BR5F, CR3B, and CR6B). Each photopoint location has been marked with a wooden peg, a green plastic waratah, or a white photopoint marker as appropriate; Table 2 lists which style of marker was used at each location. An existing survey peg was used at Crown Road Photopoint 7. Prior to 2019, digital photographs were taken with Canon EOS7D using either a Canon EF 24-105mm f/4L IS USM lens or a Canon EFS 10-22mm f/3.5-4.5 USM lens. In 2019, an Apple iPhone XS Max camera was used. The focal length was based on the area shown in previous photographs or what was most appropriate for the photograph at the time. Photographs taken in 2019 were compared with photographs taken in 2016 (Wildland Consultants 2016), or fully described if they were established during the current fieldwork. See Appendix 4 for photopoint photographs and their descriptions.
Wildland Consultants 2019: Geothermal vegetation monitoring for Te Ahi O Maui, 2019. Contract Report No. 5085a.	2019	Kawerau	A field map (scale 1:2,000) of the Te Ahi o Maui site, Te Kaukahiwi o Tirotirowhetu Scenic Reserve, and Parimahāna Scenic Reserve was prepared using BOPLASS 2018/19 aerial imagery and Google imagery (Map data: 3/3/2019 Planet.com). Vegetation and habitat types present at Te Ahi o Maui were determined from assessment of the aerial photographs and mapped using ArcGIS.	Soil temperature at 10 centimetres depth was measured at one metre intervals along each transect.	The plot is permanently marked with a fiberglass pole at the end of each transect line. The plot is 22 metres long and four metres wide. Five transects were laid from the downslope end to the upslope end of the plot and marked out by tape measures at one metre wide intervals within the plot area. Scott height-frequency (Scott 1965) was measured at one metre intervals along each transect. At each sample point the presence of each plant species was recorded in 10 centimetres height intervals alongside a modified Scott height-frequency pole with a 5 × 10 centimetre cylinder. Non-vascular plant species presence was only recorded in the 1-10 centimetre height tier. For vegetation above two metres tall, the Scott height-frequency method was not used. Instead, percent cover of each species (within the 1 × 1 metre square area within the plot) was estimated within 2-5 metre and >5 metre height tiers.	At six metre intervals, sixteen 0.5 × 0.5 metre subplots were assessed along each transect to measure plant species cover. Sub-plots were assessed between the 1 m mark and the 1.5 m mark, on the northern side of each transect (Table 2). Within each 0.5 × 0.5 metre subplot, the percent cover of each vascular plant species was estimated in two height tiers: 0-30 centimetres tall and 30-200 centimetres tall. The cover of non-vascular plant species was recorded at genus level, where possible. Ground cover variables (such as leaf litter and bare ground) were only recorded in the 0-30 centimetre height tier (when they were present)		Seven photopoints were established at Te Ahi o Maui during the 2019 field work. Eleven photopoints have already been established within the reserves (see Wildland Consultants 2018). Six additional photopoints were established at Parimahāna Scenic Reserve and Te Kaukahiwi o Tirotirowhetu Scenic Reserve during the 2019 field work. These additional photopoints enhance the existing photopoints, by increasing the extent and diversity of features covered by photopoint monitoring. Four of these photopoints are within areas of geothermally influenced vegetation, while the other two are on the edge of Parimahāna Scenic Reserve and provide a view of vegetation on the steep hillslopes. Locations of all the photopoints at Te Ahi o Maui, Parimahāna Scenic Reserve, and Te Kaukahiwi o Tirotirowhetu Scenic Reserve are shown in Figure 2. Photopoint photographs are presented in Sections 9 and 10. The location (NZTM), methods of permanent marking (where possible), and bearing (magnetic north) of each photopoint were recorded (see Table 1). A description of the vegetation present at each photopoint was recorded onto photopoint data sheets in the
Wildland Consultants 2021: Preliminary mitigation and monitoring plan to address effects on terrestrial ecology due to changes associated with ongoing energy generation from the Wairakei geothermal field. Contract report No. 5493a.	2021	Wairakei-Tauhara	The extent of geothermal vegetation in this geothermal field has also been mapped on a number of occasions, generally for Waikato Regional Council since 2000, and vegetation maps have been updated on		Monitoring transects were initially established in the Wairākei Geothermal Field in 1995 and 1996 (Burns et al. 1996) to assess potential changes within geothermal vegetation. Seven rectangular grids of 100 sample points were established at four locations; two at Craters of the Moon (referred to as			

Report Reference	Year	Geothermal Field	Site Area Measurement	Geophysical Measurements	Vegetation Methods [except plots]	Vegetation Methods [plots]	RECCE Methods	Photopoints
			various occasions (Wildland Consultants 2000, 2004, 2012, 2014b, and 2021a).		Karapiti), two at Upper Wairākei Valley (referred to as Thermal Valley), two Te Kiri O Hine Kai (referred to as Alum Lakes), and one at Te Rautehuia-Wairākei. Remeasurement and analysis of changes has so far been undertaken in 1998 (Merrett and Burns 1998), 2002 (Fitzgerald et al. 2003), 2008 (Smale et al. 2009), 2013 (Wildland Consultants 2013b), and 2017 (Wildland Consultants 2017b). During each monitoring round, soil temperatures, vegetation composition, and vegetation height have been measured at 100 sample points at each of the monitoring grids. Point occupancy, height, species richness, "nativeness", and "geothermalness" were calculated and used as indicators of geothermal vegetation integrity. Monitoring at Te Rautehuia-Wairākei was discontinued from 2008 due to invasion by blackberry. The loss of geothermalness at the Upper Wairākei Valley site may mean that these two transects are no longer in a state that is suitable for monitoring to be continued. Monitoring to assess changes in geothermal vegetation in the Tauhara Geothermal Field was initially established in 2006 (Merrett and Fitzgerald 2006) at 11 sites. Remeasurement and analysis of changes was undertaken in 2013 and 2017 (Wildland Consultants 2013c and 2017a). Photopoints are the main method used for this monitoring. The extent of geothermal vegetation in this geothermal field has also been mapped on a number of occasions, generally for Waikato Regional Council since 2000, and vegetation maps have been updated on various occasions (Wildland Consultants 2000, 2004, 2012, 2014b, and 2021a). As part of the Tauhara II resource consent, geothermal vegetation surveys are required to be undertaken at both Broadlands Road Reserve and Crown Road, within Tauhara Geothermal Field. Two vegetation monitoring plots were established in these areas in 2009 (Wildland Consultants 2009) and were remeasured in 2016 and 2019 (Wildland Consultants 2016 and 2019). Two additional plots that were established in 2016 were also remeasured in 2019. Photopoints were also initially established in 2006 (Merrett and Fitzgerald 2006) and have been compared between monitoring periods (Wildland Consultants 2016 and 2019).			
Wildland Consultants 2015: Ecological monitoring in Ngatamariki Geothermal Area, 2015. Wildland Consultants Ltd Contract Report No. 2883c. Prepared for Mighty River Power Ltd. Vol. 1 - 55 pp; Vol. 2 Attachments - 82 pp.	2015	Ngatamariki	The vegetation and habitat type map prepared in 2014 on 2014 aerial photographs (Wildland Consultants 2014) was updated and refined on 2015 aerial photographs during the site visits in 2015. The boundaries and	Soil temperatures were measured using a thermometer (accurate to 1%) at a depth of 0-10 cm, depending on the hardness of the substrate, at 1 m intervals along the four transects.	Four monitoring transects were established in 2012 according to the indicative locations provided by the Department of Conservation; with two transects at Ngatamariki North and two at Ngatamariki South. The transect locations were selected to represent the diversity of geothermal vegetation	The tape measure delineates the middle of the 1 × 1 m transect. A contiguous series of 1 × 1 m plots spanning both sides of the tape, was measured at each metre mark along the transect line. In the 1 × 1 m plot, the percent cover of all vascular plant species present in the 2-5 m, 5 12 m, 12-25 m, and >25 m vegetation tiers was	In the 0.5 × 0.5 m quadrat, the percent cover of all plant species present (vascular and non-vascular) was estimated and recorded in two vegetation tiers (<30 cm and 30 cm-2 m).	Ten permanent photopoint sites (five in Ngatamariki North and five in Ngatamariki South) were established in 2012 to monitor the range of vegetation and habitats present in the Ngatamariki Geothermal Area (locations are shown in Figure 3, and details are presented in Appendix 2).

Report Reference	Year	Geothermal Field	Site Area Measurement	Geophysical Measurements	Vegetation Methods [except plots]	Vegetation Methods [plots]	RECCE Methods	Photopoints
			descriptions of the mapped vegetation types have been further appraised, and revised where necessary, during the current study (using 2015 aerial photography) to reflect any changes in plant species composition and extent. It should be noted that aerial photographs available in 2014 and 2015 were of better quality resolution than the 2013 photographs (which were of better quality than the 2012 photographs).		at Ngatamariki. Transects were not located randomly because areas of geothermal vegetation at Ngatamariki are relatively small and discontinuous, some geothermal areas are unsafe to work in, and some plant populations and features are vulnerable to trampling disturbance.	estimated and recorded. A 0.5 × 0.5 m quadrat was placed in the lower quadrant on the left-hand side of the tape of each 1 × 1 m plot (Figure 2). In the 0.5 × 0.5 m quadrat, the percent cover of all plant species present (vascular and non-vascular) was estimated and recorded in two vegetation tiers (<30 cm and 30 cm-2 m).		Each photopoint was permanently marked using a green plastic waratah. In 2012, a series of photographs was taken at eight of the ten photopoints and one photograph was taken at the remaining two photopoints; this resulted in a total of 56 photographs. The photograph series compiled in 2012 was retaken in 2013, 2014, and 2015 but only one photograph from each photopoint was chosen for inclusion within this report to measure visible change over time. Photographs used for comparison were chosen to show the full range of geothermal vegetation and habitats present within the site. For sites where a series of photographs was taken, the comparison photograph can be changed to another photograph from the series if the view becomes obscured over time. In 2015, all photographs were taken with a Canon EOS 7D camera with a Canon EF-S 10-22 f3.5-4.5 USM lens. These photographs were taken at a 35 mm equivalent of 27 mm. The original photographs are in RAW files, but have been converted into JPG files for long-term storage. Note: A few photographs presented in Volume 2 in 2014 were taken with an Olympus µ850 SW, 35 mm lens equivalent.

PART B

Report Reference	Year	Change in Vegetation or Vegetation Condition	Plants	Threatened Plant	Plant Pests	Monitoring Frequency	Birds	Pest Animals	Notes
Given D.R. 1978. Vegetation on heated soils at Karapiti, Wairakei. *Unpublished Report. Botany Division, DSIR, Christchurch*	1978								
Given D.R. 1980: Vegetation on heated soils at Karapiti, central North Island, New Zealand, and its relation to ground. New Zealand Journal of Botany 18: 1-13.	1980								
Miller E.M. and Ecroyd C.E. 1993: Waikite Thermal Reserve: Vegetation, plant species, and special botanical features. *Report prepared for the Parks and Reserves Department of the Rotorua District Council*.	1993								
Burns B.R. and Leathwick J. R. 1995: Geothermal vegetation dynamics in Te Kopia Scenic Reserve. *Science for Conservation 18*. Department of Conservation. Wellington. 26 pp.	1995								
Burns B.R., Whaley K.J., and Whaley P.T. 1995: Thermotolerant vegetation of the Tauhara Geothermal Field. *Landcare Research Contract Report: LC9596/020*.	1995								
Burns B.R., Whaley K.J., and Whaley P.T. 1996: Establishment of monitoring grids within geothermal vegetation, Wairakei Geothermal Field. *Landcare Research Contract Report: LC9596/135*.	1996	A single summed height-frequency value can be derived for each species at each grid by summing its frequency in each 10 cm height category. This 'biomass index value' can then be used in future remeasurements to test for statistically significant changes between measurements using the Pearson chi-squared test of independence (Dickinson et al. 1992, Burns 1996).							
Burns B.R. 1997b: Vegetation change along a geothermal stress gradient at the Te Kopia steamfield. *Journal of the Royal Society of New Zealand 2*: 279-294.	1997	The stand compositional data (all species, and cryptogams only) were classified using two-way indicator species analysis (TWINSPAN: Hill et al. 1975). Names for assemblages followed the conventions of Atkinson (1985). An indirect ordination was also performed on these data using detrended correspondence analysis (DECORANA: Hill & Gauch 1980). Spearman's rank order correlation was then used to correlate the DECORANA stand scores with stand environmental data variables that were continuous. The influence of topography was examined by an analysis of DECORANA stand score variance between different topographic units.							
Merrett M.F. and Burns B. 1997: Biological assessment of the Rotokawa Geothermal Field. *Landcare Research Contract Report: LC 9798/019*.	1997								
Merrett M.F. and Burns B.R. 1998a: Thermotolerant vegetation of the Ohaaki Geothermal Field. *Landcare Research Contract Report: LC9798/084*.	1998	Emphasis on qualitative assessment							
Merrett M.F. and Burns B.R. 1998c: Wairakei Geothermal Field vegetation monitoring: changes after two years. *Landcare Research Contract Report: LC9798/089*.	1998	A single summed height-frequency value was derived for each species at each grid by summing its frequency in each 10 cm height category. This 'biomass index value' can then be used to test for statistically significant changes between measurements using the				5 years for remeasurement, two years for maintenance and photographs.			

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		Pearson chi-squared test of independence (Dickinson et al. 1992; Burns et al. 1996).							
Merrett M.F. and Clarkson B.R. 1999: Definition, description and illustrations of geothermally influenced terrestrial and emergent wetland vegetation. *Landcare Research Contract Report: LC9900/022*.	1999								
Wildland Consultants 2000: Geothermal vegetation of the Waikato Region. *Wildland Consultants Ltd Contract Report No. 297*. 178 pp.	2000								
Merrett M.F., Burns B.R., and Fitzgerald N.B. 2003: Reassessment of geothermal vegetation at Ohaaki Geothermal Field and establishment of monitoring transects. *Landcare Research Contract Report: LC0304/014*.	2003		Noting plant species encountered and main vegetation associations, particularly focussing on geothermal vegetation in the area.						
Wildland Consultants 2003: Geothermal vegetation of the Waikato Region - Revised and expanded 2003. *Wildland Consultants Ltd Contract Report No. 664*. Prepared for Environment Waikato. 225 pp.	2003								
Merrett M.F. and Fitzgerald N.B 2004: Changes in geothermally influenced vegetation at Mokai Geothermal Field 5 years after the start of geothermal energy extraction. *Landcare Research Contract Report: LC0304/084*. 34 pp.	2004	The colour and texture of current geothermal vegetation was used to interpret the extent of geothermal vegetation present in 1941 and 1984 relative to static landscape features, e.g., rock outcrops, roads, and sinter terraces. This information was then used to assess changes over different time intervals.	At each site, all vascular and non-vascular plant species encountered were recorded and vegetation structure noted						
Wildland Consultants 2004c: Geothermal Vegetation of the Waikato Region - Revised 2004. *Wildland Consultants Ltd Contract Report No. 896*. Prepared for Environment Waikato. 244 pp.	2004								
Merrett M. and Fitzgerald N. 2006. Thermotolerant vegetation of the Tauhara Geothermal Field. *Landcare Research Contract Report LC0506/118*. Prepared for Contact Energy. Landcare Research, Hamilton. 28 pp.	2006								
Wildland Consultants 2006: Field evaluations of five geothermal sites, Waikato Region, June 2006. *Wildland Consultants Ltd Contract Report No. 1403*. Prepared for Environment Waikato. 28 pp.	2006								
Bycroft C.M. and Beadel S.M. 2007: Distribution and density of *Christella* sp. 'thermal' *Cyclosorus interruptus*, and *Hypolepis dicksonioides*, at geothermal sites in the Waikato Region. *Wildland Consultants Ltd Contract Report No. 1611*.	2007			Informal walk-through survey					
Wildland Consultants 2007: Requirements for the protection and enhancement of 'Craters of the Moon' - a geothermal natural area and tourist attraction near Taupō. *Wildland Consultants Ltd Contract*	2007								

Report Reference	Year	Change in Vegetation or Vegetation Condition	Plants	Threatened Plant	Plant Pests	Monitoring Frequency	Birds	Pest Animals	Notes
Report No. 1785. Prepared for Department of Conservation. 40 pp.									
Wildland Consultants 2007a: Evaluation and mapping of selected geothermal sites for minor variation to Waikato Regional Plan - Geothermal vegetation and geophysical properties: February 2007. *Wildland Consultants Ltd Contract Report No. 1588*. Prepared for Environment Waikato. 57 pp.	2007								
Wildland Consultants 2007b: Field evaluations of nine geothermal sites, Waikato Region, June 2007. *Wildland Consultants Ltd Contract Report No. 1619*. Prepared for Environment Waikato. 56 pp.	2007								
Wildland Consultants 2007c: Requirements for the protection and enhancement of Broadlands Road Scenic Reserve. *Wildland Consultants Ltd Contract Report No. 1789*. Prepared for Department of Conservation. 37 pp.	2007								
Mitchell Partnerships 2009: Ngatamariki Ecological Report. Prepared for Rotokawa Joint Venture Ltd.	2009								
Smale, MC, Fitzgerald, NB, Mason, NWH, Cave, SA 2009. Wairakei Geothermal field vegetation monitoring: Changes between 1995 and 2008. Landcare Research Contract Report: LC0809/116	2009	Five indicators of geothermal vegetation health were calculated for each measurement point of each grid. Vegetation point occupancy (the number of 10 cm vertical intervals occupied— a surrogate for foliage biomass of vegetation at a site), vegetation height, species richness, "nativeness" (the proportion of point occupancy comprised of native species), and "geothermalness" were calculated for each grid for each measurement year. We define geothermalness as the proportion of point occupancy comprised of the three vascular species which are present and highly characteristic of geothermal vegetation in the Wairakei area— prostrate kānuka (Kunzea ericoides var. microflora), arching clubmoss (Lycopodiella cernua), and thermal ladder fern (Nephrolepis flexuosa).				Soil-temperatures: biennially. Vegetation: 4-yearly.			ANOVA with permutation tests, PERMANOVA (Anderson 2005), was used to test for significant relationships between point occupancy, vegetation height, species richness, nativeness and geothermalness and measurement years. PERMANOVA has the advantage that it does not require data to be normally distributed, and provides a more powerful test than a standard F
Wildland Consultants 2009: Establishment of Geothermal Vegetation Monitoring plots. Contract Report No. 2323. Prepared for GNS. 40 pp.	2009								Data reported in van Manen and Reese (2012) I think -- check
Wildland Consultants 2009a: Orakei Korako Cave and Thermal Park - Interpretation and restoration. *Wildland Consultants Ltd Contract Report No. 2034*. 23 pp.	2009								Not a monitoring orientated report
Wildland Consultants 2009c: Wilding pine control at Orakei Korako cave and thermal park. *Wildland Consultants Ltd Contract Report No. 2333*. Prepared for Wairakei Environmental Mitigation Charitable Trust. 12 pp.	2009								
Wildland Consultants 2011: Geothermal vegetation of the Waikato Region - An update based on 2007 aerial photographs. *Wildland Consultants Ltd Contract Report*	2011								

Report Reference	Year	Change in Vegetation or Vegetation Condition	Plants	Threatened Plant	Plant Pests	Monitoring Frequency	Birds	Pest Animals	Notes
No. 2348. Prepared for Waikato Regional Council. 515 pp.									
Wildland Consultants 2011a: Priorities for pest plant control, pest animal control, and fencing at geothermal sites in the Waikato Region in 2011. *Wildland Consultants Ltd Contract Report No. 2755*. Prepared for Waikato Regional Council.	2011								Desktop exercise based on previous survey work
Wildland Consultants 2011b: Ranking of sites with geothermal vegetation and habitats for biodiversity management in the Waikato Region. Wildland Consultants Ltd Contract Report No. 2756. Prepared for Waikato Regional Council.	2011								Desktop exercise
van Manen SM, Reeves R. 2012: An Assessment of Changes in Kunzea ericoides var. microflora and Other Hydrothermal Vegetation at the Wairakei–Tauhara Geothermal Field, New Zealand. Environmental Management 50: 766-786.	2012	The biomass index value can be used to test for statistically significant changes between measurements using the v2 test of independence (e.g., Dickinson and others 1992; Merrett and Burns 1998). Although a nonparametric test, it does assume independent random sampling of the data. In this study, the Ashwood Park and Broadlands Road plots were randomly established. The Karapiti and Geyser Valley plots were pre-existing but assumed to be originally randomly established. The Scott height-frequency method assumes that species occur independently at each sampling point.							Excellent summary of historical changes in field hydrology.
Wildland Consultants 2012: Geothermal vegetation of the Waikato Region - an update based on 2007 aerial photographs. Wildland Consultants Ltd Contract Report No. 2348. Prepared for Waikato Regional Council. 528 pp.	2012	Field assessments addressed the following components: the extent and type of vegetation present; indigenous flora (including the presence of any threatened plants); fauna present (which included a literature review for each site); current condition; invasive exotic plants; human impacts; grazing; adjoining land use and management requirements.					1		
Wildland Consultants 2013: Ecological monitoring of geothermal vegetation in the Wairakei geothermal field 2013. *Wildland Consultants Ltd Contract Report No. 3109*. Prepared for Contact Energy. 21 pp.	2013	Following the methods of Smale et al. (2009), five indicators of geothermal vegetation health were calculated for each measurement point of each grid in 2013: · Vegetation point occupancy - the number of 10 cm vertical intervals occupied by vegetation. This is a surrogate for foliage biomass, and geothermal vegetation is typically characterised by relatively low scores; · In 2013 vegetation height was calculated as the mid-point of the maximum height interval occupied. It should be noted that the methods used to measure and/or calculate vegetation height in 2008 were not available and therefore some caution should be applied to the interpretation of differences between monitoring events; · Vascular plant species richness - the number of vascular plant species present; · "Nativeness" - the proportion of point occupancy comprised of native species; · "Geothermalness" - the proportion of point occupancy comprising "geothermal vegetation". For the purposes of this assessment "geothermal vegetation" is defined as cover of prostrate kānuka (Kunzea ericoides var. microflora), arching clubmoss (Lycopodiella cernua), and thermal ladder fern (Nephrolepis flexuosa). These three vascular							

Report Reference	Year	Change in Vegetation or Vegetation Condition	Plants	Threatened Plant	Plant Pests	Monitoring Frequency	Birds	Pest Animals	Notes
		species are present and are highly characteristic of geothermal vegetation in the Wairakei area.							
Wildland Consultants 2013: Ecological assessment and ecological restoration advice, Otumuheke Stream, Taupō. *Wildland Consultants Ltd Contract Report No. 3082*. Prepared for Waikato Regional Council. 73 pp.	2013			Key populations of threatened or 'At Risk' plants (as classified in de Lange et al. 2009) were identified and described.	The distribution pattern of weeds that threaten geothermal vegetation and habitats were mapped		All avifauna heard or seen were recorded		
Wildland Consultants 2014: Ranking of geothermal ecosystems for biodiversity management in the Waikato Region. Wildland Consultants Ltd Contract Report No. 2756a. Prepared for Waikato Regional Council. 19 pp	2014								Desktop exercise
Wildland Consultants 2014: Geothermal vegetation of the Waikato Region, 2014. Wildland Consultants Ltd Contract Report No. 3330. Prepared for Waikato Regional Council. 526 pp.	2014				1		1		
Wildland Consultants 2015: Application of ecological indicators for the extent, condition, and protection level of geothermal habitats, Waikato Region. Contract Report No. 3504a. Prepared for Waikato Regional Council. 22 pp.	2015								Indicator framework for geothermal vegetation in Waikato Region, encompassing all data derived from geothermal monitoring
Wildland Consultants 2015: Ecological effects of proposed steamfield expansion at the Rotokawa geothermal field, Taupō. Contract Report No. 3623.	2015	All analyses were carried out using the software R (version 4.1.2; R core team, 2021) and the packages 'nlme'2 and 'ggplot23'. Students' t-tests and mixed effects models were used to determine differences between the two years (2017 and 2021), where significance was determined with p-values (α < 0.05). Normality and heterogeneity of data were determined using histograms, boxplots and Shapiro-wilks tests, model fit was determined through diagnostic plots assessing heterogeneity of residuals versus fitted values.	A list of all vascular plant species recorded within geothermal vegetation and habitats at the site was complied. Annotations were used to indicate the relative abundance of these species across the site. These are defined as: • Rare (R): few individuals, not locally abundant anywhere within the site. • Occasional (O): scattered occurrence across the site, or locally at greater abundance. Contract Report No. 3623c - Volume 1 • Frequent (F): occurring widely across the site, but not dominant. • Abundant (A): dominates a vegetation tier across a substantial part of the site.				All bird species seen or heard at the site during the fieldwork were recorded		
Wildland Consultants 2016: Application of ecological indicators for the extent, condition, and protection level of geothermal habitats, Waikato Region. Wildland Consultants Ltd Contract Report No. 3504b. Prepared for Waikato Regional Council. 39 pp.	2016								Summary of indices for all Waikato Sites, based on a compilation of data collected as part of other reports.
Wildland Consultants 2016: Geothermal monitoring at Broadlands Road Reserve and Crown Road, Taupō, 2016. Wildland Consultants Ltd Contract Report No. 3109b. Prepared for Contact Energy. 40 pp.	2016						All bird species seen or heard during fieldwork within the study area were recorded.		
Wildland Consultants 2016: Ecological monitoring in Ngatamariki geothermal area, 2016. Volume 1. Contract Report No. 2883d. Prepared for Mercury New Zealand Ltd.	2016		In 2012, vascular plant taxa present within geothermal vegetation and habitats were recorded and an annotated list of vascular plant species present was prepared, indicating their relative abundance, i.e. Rare (R), Occasional (O), Frequent (F), and	Populations of rare or geothermal indicator species at Ngatamariki were identified in 2012, and remeasured again in 2013, 2014, 2015, and 2016. In 2013 and 2014, additional populations of rare or geothermal indicator species that had not previously been measured were described and added to the	Over the course of the 2016 field visits, notes were made on existing and potential threats to the vegetation and geothermal habitat. Examples of threats include pest© 2016 8 Contract Report No. 2883d -	2 years			

Report Reference	Year	Change in Vegetation or Vegetation Condition	Plants	Threatened Plant	Plant Pests	Monitoring Frequency	Birds	Pest Animals	Notes
			Abundant (A) as follows: Rare: Few individuals, not locally abundant anywhere within the site. Occasional: Scattered occurrence across the site, or locally at greater abundance. Frequent: Occurring widely across the site, but not dominant. Abundant: Dominates a vegetation tier across most of the site Plant species were identified as to whether they occurred in Ngatamariki North or Ngatamariki South. This annotated list was checked and updated where necessary during the current study and is presented in Appendix 3. The relative abundance categories were updated during the 2016 survey. A list of common non-vascular plant species was also compiled for the site	list of key indicator species to be monitored. In 2015, one additional population of Psilotum nudum was found. In 2016, one additional population of geothermal kānuka and one additional population of Lycopodiella cernua were found1. For each population of each species, notes were made on the health, population size, and extent of each population, and any new populations of the key species were recorded. Rare or geothermal indicator species at Ngatamariki are as follows: arrow grass (Triglochin striata), Cyclosorus interruptus, Dicranopteris linearis, Lycopodiella cernua, geothermal kānuka, Psilotum nudum, and the moss (Campylopus sp.). The following measurements were made in 2012, 2013, 2014, 2015, and 2016, if the populations were located, to allow changes in the number, dimensions, and vigour of individuals of important plant species to be compared over time: · The location and extent of each plant population was mapped and its GPS coordinates recorded populations were located, to allow changes in the number, dimensions, and vigour of individuals of important plant species to be compared over time: · The location and extent of each plant population was mapped and its GPS coordinates recorded· The number of fronds and/or separate clumps and maximum height within a population were recorded. · Where individual tagging was not possible or practical, the size structure of the whole population was estimated. · The health and vigour of each population was assessed. · Animal browse (if any) was recorded. · Age structures of each population were estimated (number of adults, number of juveniles). · Fertility was recorded, e.g., spores or inflorescence stages present. · Key threats and management recommendations for each population were assessed. In 2016, the following was searched for: four populations of *Cyclosorus interruptus*; four populations of geothermal kānuka; four (of five) populations of Psilotum nudum; two populations of arrow grass and *Campylopus* sp.; and one population of *Dicranopteris linearis* and *Lycopodiella cernua*	Volume 1 plants, pest animal damage to vegetation, plantation forestry operations (e.g., harvesting), herbicide spray, trampling, rubbish, and fire				
Wildland Consultants 2016: Relationships between ground and aerial photography and geothermal vegetation at craters of the moon geothermal area, Waikato. Contract Report No. 4010.	2016	Stressed geothermal vegetation (identified subjectively through percentage cover of dead foliage), and in particular vegetation dominated by geothermal kānuka, can be identified by ground based NDVI values at a relatively small scale. This suggests that aerial NDVI may also be able to determine geothermal vegetation stress.							UAV photography
Wildland Consultants 2017: Ecological monitoring of geothermal vegetation in the Ohaaki geothermal field 2017. Wildland Consultants Ltd Contract Report No. 3109e. Prepared for Contact Energy. 41 pp.	2017								
Beadel S, Shaw W, Bawden R, Bycroft C, Wilcox F, McQueen J, Lloyd K. 2018: Sustainable management of geothermal vegetation in the Waikato Region, New Zealand, including	2018								Review of monitoring

Report Reference	Year	Change in Vegetation or Vegetation Condition	Plants	Threatened Plant	Plant Pests	Monitoring Frequency	Birds	Pest Animals	Notes
application of ecological indicators and new monitoring technology trials. Geothermics 73: 91-99.									
Reeves RR, Wilke M, Cashmore P, Macdonald N, Thompson K. 2018: Physical and ecological effects of rehabilitating the geothermally influenced Waikite Wetland, New Zealand. Journal of Environmental Management 228: 279-291.	2018								
Wildland Consultants 2019: Baseline monitoring at 39A2A (Umupokapoka) Lagoon, Kawerau -2019. Contract Report No. 5202a.	2019		A list of all vascular and non-vascular plant species (bryophytes and lichens) observed during the field work at Umupokapoka Lagoon was compiled. Vascular plants were generally identified to species level in the field. Non-vascular plants were often identified to genus level in the field, but collection of samples was generally required to enable species level identification. Other fauna observed were noted.				A list of all avifauna observed during the field work at Umupokapoka Lagoon was compiled.		
Wildland Consultants 2019: Geothermal monitoring at Broadlands Road Reserve and Crown Road, Taupō, 2019. Contract Report No. 3109f. Prepared for Contact Energy. 73 pp.	2019	The significance of differences in mean soil temperature, cover of species, and ground cover variables in RECCE plots between years (2016 and 2019) was determined using two sample paired t-tests, with α = 0.05. Contract Report No. 3109f: Simple comparisons were made of Scott height frequency data between plots and years. The total occurrence of geothermal kānuka (Kunzea tenuicaulis) foliage in each height interval was presented as a kite diagram for each plot (cf. Dickinson et al. 1992), and visual comparisons were made between plots and years. An indicator of biomass of geothermal kānuka, referred to as "Biomass Index", was calculated from the summed height frequency values for geothermal kānuka. This method was based on those used by Dickinson et al. (1992). A value was calculated for the 0-0.3 metres, 0.3-1 metre, and >1 metre height tiers, as well as a total value for data from all height tiers. Line graphs were prepared, and visual comparisons were made between plots and years.			Existing and potential threats to geothermal vegetation, habitats, and geothermal features were recorded during field work, data collection, and monitoring.				
Wildland Consultants 2019: Geothermal vegetation monitoring for Te Ahi O Maui, 2019. Contract Report No. 5085a.	2019		A list of all vascular and non-vascular plant species (bryophytes and lichens), and avifauna observed during the field work at Te Ahi o Maui was compiled.	All four populations of rare or geothermal indicator plant species that were found at Te Ahi o Maui during the Year 1 monitoring (see Table 3) were relocated during the 2021 field work and reassessed. The following species were assessed at Te Ahi o Maui during Year 1: dwarf mistletoe (Korthalsella salicornioides; Threatened-Nationally Critical), Dicranopteris linearis (Threatened-Nationally Endangered), geothermal kānuka (Threatened-Nationally Endangered), and Cheilanthes sieberi (Not Threatened). For each population, notes were recorded on their location (NZTM) and extent, height, health and vigour, any animal browse evident, age structure, fertility (presence of flowers or spores), and population size. Photographs were taken. Key threats and management recommendations for each population were assessed. Notes on these populations were then compared between			A list of all avifauna observed during the field work at Te Ahi o Maui was compiled.		

Report Reference	Year	Change in Vegetation or Vegetation Condition	Plants	Threatened Plant	Plant Pests	Monitoring Frequency	Birds	Pest Animals	Notes
				years. Records for each population are presented in Appendix 5					
Wildland Consultants 2021: Preliminary mitigation and monitoring plan to address effects on terrestrial ecology due to changes associated with ongoing energy generation from the Wairakei geothermal field. Contract report No. 5493a.	2021								Excellent summary of contemporary monitoring context.
Wildland Consultants 2015: Ecological monitoring in Ngatamariki Geothermal Area, 2015. Wildland Consultants Ltd Contract Report No. 2883c. Prepared for Mighty River Power Ltd. Vol. 1 - 55 pp; Vol. 2 Attachments - 82 pp.	2015		Plant species were identified as to whether they occurred in Ngatamariki North or Ngatamariki South. This annotated list was checked and updated where necessary during the current study and is presented in Appendix 3. The relative abundance categories were updated during the 2015 survey.	Populations of rare or geothermal indicator species at Ngatamariki were identified in 2012, and remeasured again in 2013, 2014 and 2015. In 2013 and 2014, additional populations of rare or geothermal indicator species that had not previously been measured were described and added to the list of key indicator species to be monitored. In 2015, one additional population of *Psilotum nudum* was found. For each population of each species, notes were made on the health, population size, and extent of each population, and any new populations of the key species were recorded. Rare or geothermal indicator species at Ngatamariki are as follows: arrow grass (*Triglochin striata*), *Cyclosorus interruptus*, *Dicranopteris linearis*, *Lycopodiella cernua*, geothermal kānuka, *Psilotum nudum*, and the moss (*Campylopus clavatus*).	Over the course of the 2015 field visits, notes were made on existing and potential threats to the vegetation and geothermal habitat. Examples of threats include pest plants, pest animal damage to vegetation, plantation forestry operations (e.g., harvesting), overspray of herbicide, trampling, rubbish, and fire.		All bird species seen or heard while on site were recorded		

Appendix 2: Breakdown of broad geothermal hydroclass and vegetation groups within each site ordered by geothermal field and ranked by area of geothermal vegetation, Waikato Region (from Wildland Consultants 2011)

Site Name	Site Number	Ecological District	Hydroclass/Vegetation Grouping					Total Site Area (Geothermal Vegetation and Geothermal Water) (ha)	Size Rank for Extent of Geothermal Vegetation within the Waikato Region (by Geothermal Field)
			Geothermal Water (ha)	Geothermal Vegetation			Total Geothermal Vegetation (ha)		
				Nonvegetated Raw-Soilfield (ha)	Terrestrial Vegetation (ha)	Emergent Wetland (ha)			
Horohoro Geothermal Field									<0.1 ha
Horohoro	HHV01	Atiamuri	<0.1		<0.1		<0.1	<0.1	
		Total	**<0.1**		**<0.1**		**<0.1**	**<0.1**	
Waikite Geothermal Field									7
Waikite Valley	WAV01	Atiamuri	1.2	0.3	18.6	5.6	24.6	25.8	
Northern Paeroa Range	WAV02	Atiamuri		0.3			0.3	0.3	
		Total	**1.2**	**0.6**	**18.6**	**5.6**	**24.9**	**26.1**	
Waiotapu Geothermal Field									1
Maungaongaonga	WTV01	Atiamuri		0.7	8.4		9.1	9.1	
Ngapouri	WTV02	Atiamuri	0.5	<0.1	3.1		3.1	3.6	
Waiotapu North	WTV03	Atiamuri	2.9	4.6	41.3		45.8	48.8	
Maungakakaramea (Rainbow Mountain)	WTV04	Atiamuri/Rotorua Lakes	3.4	4.3	46.2		50.6	54.0	
Waiotapu South	WTV05	Atiamuri	20.6	8.4	77.8	26.3	112.4	133.0	
		Total	**27.4**	**18.0**	**176.7**	**26.3**	**221.0**	**248.4**	
Mokai Geothermal Field									10
Whakamaru	MKV01	Atiamuri		<0.1			<0.1	<0.1	
Waipapa Stream	MKV02	Atiamuri			1.1		1.1	1.1	
Tirohanga Road	MKV03	Atiamuri	0.3	<0.1	0.1		0.2	0.5	
Paerata Road	MKV04	Atiamuri	0.2	0.4	1.3		1.7	1.8	
		Total	**0.5**	**0.4**	**2.5**		**2.9**	**3.4**	
Atiamuri Geothermal Field									12
Upper Atiamuri West	ATV01	Atiamuri			<0.1		<0.1	<0.1	
Whangapoa Springs	ATV02	Atiamuri	<0.1	<0.1	<0.1		0.1	0.1	
Matapan Road	ATV03	Atiamuri			<0.1		<0.1	<0.1	

Site Name	Site Number	Ecological District	Hydroclass/Vegetation Grouping					Total Site Area (Geothermal Vegetation and Geothermal Water) (ha)	Size Rank for Extent of Geothermal Vegetation within the Waikato Region (by Geothermal Field)
				Geothermal Vegetation					
			Geothermal Water (ha)	Nonvegetated Raw-Soilfield (ha)	Terrestrial Vegetation (ha)	Emergent Wetland (ha)	Total Geothermal Vegetation (ha)		
		Total	**<0.1**	**<0.1**	**<0.1**		**0.1**	**0.2**	
Te Kopia Geothermal Field									5
Te Kopia	TKV01	Atiamuri	1.1	5.5	48.9	4.4	58.8	59.9	
Murphy's Springs	TKV02	Atiamuri			0.2		0.2	0.2	
Te Kopia Northwest	TKV03	Atiamuri		<0.1			<0.1	<0.1	
Te Kopia West Mud Pools	TKV04	Atiamuri			<0.1		<0.1	<0.1	
Te Kopia Red Stream	TKV05	Atiamuri			0.2		0.2	0.2	
Mangamingi Station	TKV06	Atiamuri		0.1	0.4		0.5	0.5	
		Total	**1.1**	**5.6**	**49.8**	**4.4**	**59.8**	**60.9**	
Orakeikorako Geothermal Field									6
Waihunuhunu	OKV01	Atiamuri	2.3		0.3	2.7	3.0	5.3	
Akatarewa Stream	OKV02	Atiamuri			1.4		1.4	1.4	
Orakeikorako	OKV03	Atiamuri	<0.1	2.1	40.3		42.4	42.4	
Red Hills	OKV04	Atiamuri	0.1	0.3	11.1		11.4	11.5	
Akatarewa East	OKV05	Atiamuri		<0.1	<0.1		<0.1	<0.1	
		Total	**2.5**	**2.3**	**53.2**	**2.7**	**58.2**	**60.7**	
Ngatamariki Geothermal Field									11
Waikato River Springs	NMV01	Atiamuri	0.2	<0.1		0.4	0.4	0.6	
Ngatamariki	NMV02	Atiamuri	0.2	0.4	1.0	<0.1	1.5	1.7	
		Total	**0.4**	**0.4**	**1.0**	**0.4**	**1.9**	**2.3**	
Whangairorohea Geothermal Field									<0.1 ha
Whangairorohea	WGV01	Atiamuri	<0.1		<0.1		<0.1	<0.1	
		Total	**<0.1**		**<0.1**		**<0.1**	**<0.1**	
Reporoa Geothermal Field									9
Longview Road	RPV01	Atiamuri	0.2	1.5	1.9		3.4	3.6	
Wharepapa Road	RPV02	Atiamuri	0.2	1.2	2.2		3.3	3.5	
Golden Springs	RPV03	Atiamuri	<0.1		0.1	0.3	0.5	0.5	
		Total	**0.4**	**2.6**	**4.4**	**0.3**	**7.2**	**7.6**	
Ohaaki Geothermal Field									8

Site Name	Site Number	Ecological District	Hydroclass/Vegetation Grouping					Total Site Area (Geothermal Vegetation and Geothermal Water) (ha)	Size Rank for Extent of Geothermal Vegetation within the Waikato Region (by Geothermal Field)
			Geothermal Water (ha)	Geothermal Vegetation			Total Geothermal Vegetation (ha)		
				Nonvegetated Raw-Soilfield (ha)	Terrestrial Vegetation (ha)	Emergent Wetland (ha)			
Ohaaki Steamfield West	OHV01	Atiamuri	0.1	2.2	9.5		11.7	11.8	
Ohaaki Steamfield East	OHV02	Atiamuri		3.1	3.7		6.8	6.8	
		Total	**0.1**	**5.3**	**13.2**		**18.5**	**18.6**	
Wairakei-Tauhara Geothermal Field									2
Otumuheke Stream	THV01	Atiamuri			2.3		2.3	2.3	
Spa Thermal Park	THV03	Atiamuri		<0.1	0.1		0.1	0.1	
Broadlands Road	THV04	Atiamuri	<0.1	4.6	25.2		29.8	29.8	
Crown Park	THV05	Taupō		0.1	0.6		0.7	0.7	
Crown Road	THV06	Taupō/Atiamuri		3.7	13.8		17.5	17.5	
Waipahihi Valley	THV07	Taupō			0.3		0.3	0.3	
Te Rautehuia	WKV01	Atiamuri		0.5	7.2		7.7	7.7	
Te Rautehuia Stream	WKV02	Atiamuri		0.5	1.6		2.1	2.1	
Upper Wairakei Stream (Geyser Valley)	WKV03	Atiamuri		0.2	4.5		4.7	4.7	
Wairakei Borefield	WKV04	Atiamuri			<0.1		<0.1	<0.1	
Te Kiri O Hine Kai Stream Catchment/Wairoa Hill	WKV05	Atiamuri	0.2	3.3	36.8		40.1	40.3	
Lower Wairakei Stream	WKV06	Atiamuri	<0.1		<0.1		<0.1	<0.1	
Karapiti Forest	WKV07	Atiamuri			0.6		0.6	0.6	
Hall of Fame Stream	WKV08	Atiamuri			0.1		0.1	0.1	
Waipouwerawera Stream/Tukairangi	WKV09	Atiamuri			0.1		0.1	0.1	
Craters of the Moon	WKV10	Atiamuri		1.5	43.1		44.6	44.6	
		Total	**0.3**	**14.4**	**136.3**		**150.7**	**151.0**	
Rotokawa Geothermal Field									3
Rotokawa North	RKV01	Atiamuri	<0.1	3.3	31.1		34.3	34.4	
Lake Rotokawa	RKV02	Atiamuri	67.9	13.1	56.2		69.4	137.3	
		Total	**68.0**	**16.4**	**87.3**		**103.7**	**171.7**	
Tokaanu-Waihi-Hipaua Geothermal Field									4

Site Name	**Site Number**	**Ecological District**	**Hydroclass/Vegetation Grouping**					**Total Site Area (Geothermal Vegetation and Geothermal Water) (ha)**	**Size Rank for Extent of Geothermal Vegetation within the Waikato Region (by Geothermal Field)**
			Geothermal Water (ha)	**Geothermal Vegetation**			**Total Geothermal Vegetation (ha)**		
				Nonvegetated Raw-Soilfield (ha)	**Terrestrial Vegetation (ha)**	**Emergent Wetland (ha)**			
Hipaua	TOV02	Tongariro		0.4	11.0		11.3	11.3	
Tokaanu Lake Shore Wetland	TOV05	Taupō/ Tongariro	3.3			39.1	39.1	42.4	
Maunganamu West	TOV07	Taupō/ Tongariro				0.6	0.6	0.6	
Tokaanu Thermal Park	TOV08	Tongariro	0.2	0.1	6.7	0.8	7.6	7.8	
Tokaanu Urupa Mud Pools	TOV09	Taupō			<0.1		<0.1	<0.1	
Maunganamu East	TOV10	Taupō				<0.1	<0.1	<0.1	
Maunganamu North Wetland	TOV11	Taupō				0.9	0.9	0.9	
Tokaanu Tailrace Canal	TOV14	Tongariro				<0.1	<0.1	<0.1	
		Total	**3.5**	**0.5**	**17.7**	**41.4**	**59.5**	**63.0**	
Tongariro Geothermal Field									8
Te Maari Craters	TGV01	Tongariro		4.9			4.9	4.9	
Ketetahi	TGV02	Tongariro		8.2			8.2	8.2	
Emerald Lakes	TGV03	Tongariro	0.8	11.3			11.3	12.1	
Red Crater	TGV04	Tongariro		0.7			0.7	0.7	
		Total	**0.8**	**25.1**			**25.1**	**25.9**	
Grand Total			**106.2**	**91.8**	**560.7**	**81.1**	**733.6**	**839.88**	

Appendix 3: Participants of geothermal ecosystem monitoring methods workshop, 25 February 2022

Surname	**First name**	**Organisation**
Beadel	Sarah	Wildland Consultants
Burns	Bruce	University of Auckland
Bycroft	Chris	Wildland Consultants
Cashmore	Paul	Department of Conservation
Dean	Shay	Bay of Plenty Regional Council
Dutton	Paul	Waikato Regional Council
Eynon-Richards	Nick	Mercury
Forrest	Evelyn	Ngāti Tahu-Ngāti Whāoa Runanga Trust
Kleven	Nicole	Mercury
Luketina	Katherina	Waikato Regional Council
McQueen	Jo	Wildland Consultants
Merring	John	Mercury
Renner	Matthew	Wildland Consultants

Apologies

Clarkson	Bruce	Waikato University
Fitzgerald	Neil	Landcare Research
Wiser	Susan	Landcare Research