

Invertebrate Macro-Fauna in Geothermal Soils under Native Vegetation in the Waikato Region, New Zealand

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ABSTRACT

Growing human populations are putting increasing social and economic pressures on geothermal ecosystems, potentially compromising the delivery of environmental services. Understanding linkages between and within ecosystems to maintain their integrity is important for effective management. The initial stages of the development of a decision tool to direct ecological and economic decision making is reported here.

A pilot survey was undertaken to provide baseline descriptive information of soil macro-fauna under native vegetation on geothermal soils in the Waikato region, and also to develop a provisional ranking system to rate the quality and disturbance (human induced) at individual geothermal sites. Descriptors including vegetation and soil macro-fauna did not correlate with soil temperatures. Habitat threats particularly from human activities were identified as significant. Structural and functional relationships within the geothermal soil environment are identified as fragile and little-studied in the context of New Zealand geothermal systems. Site uniqueness with respect to vegetation and soil macro-fauna indicates that individual site plans to facilitate connectivity and design buffers to increase resilience of ecosystem services is necessary. The site quality ranking tool has been established to be suitable for purpose and could form the basis for ranking site quality from the basis of human and pest perturbations.

The next stage of this project, to develop a tool (geothermal site biodiversity management tool) designed to inform decision making as to the allocation of resources to preserve geothermal site biodiversity is described. Based on the site ranking system this tool would be risk analysis based. It is envisaged that individual sites may be comparatively evaluated as to the probability of sustainably managing biodiversity and ecological services.

1. INTRODUCTION

Ecological decision-making should be based around the preservation of ecological processes and of habitat, which includes the flora and soil and its macro- and micro-fauna. At present little is understood of the detail of these systems. However, decisions based on site quality may form the basis for management decisions under a precautionary principle while the details are researched. Economic decision-making should include the value of ecosystem services as well as commercial potential.

The objective of preserving the biodiversity of geothermal habitats must address system functionality and resilience to ensure the provision of ecosystem services. To this end, buffering from external influences deleterious to the health of the flora and soil and recognising the role of connectivity to ensure services (e.g. pollination) that may not be contained within site would be components of a management strategy.

Ecological data to form a baseline for soil fauna in geothermal areas is singularly lacking for the Waikato region. Soil temperature surveys undertaken by Thompson (1965) indicate a wide range of influences in terms of extent and intensity from geothermal features. Recording the range of endemic flora and surface dwelling fauna in close proximity to geothermal features by Boothroyd and Browne (2006) creates baseline data for this environment, but other than a soil macro-fauna survey of 12 geothermal features by Willoughby (2012) there is little specific information available about soil fauna in geothermal areas of the Waikato region. That survey was restricted to soils under pasture to simplify the interpretation of the data by reducing dietary induced complexities of soil fauna introduced by complex vegetative cover. Individual site characteristics were so variable to preclude any standardised soil macro-fauna interpretation, either spatially or temporally, within a geothermal environment.

The Waikato Regional Council (WRC), through the process of identifying Significant Natural Areas (SNAs), has created an inventory of natural habitat in the Waikato region. Geothermal vegetation is mapped into three broad categories; non-vegetated raw soil field; emergent wet land; and terrestrial vegetation (Bycroft et al 2007). A process towards a better understanding of the functionality is required with a view to achieving better management and understanding the linkages required to sustain what at present comprises a mosaic of unconnected geothermal habitats. We report on a survey designed to provide baseline descriptive information of soil macro-fauna under native vegetation in geothermal soils in the Waikato region. A ranking system is presented to rate the quality and disturbance (human induced) at individual geothermal sites. An outline is given of the next stage, to develop a geothermal site biodiversity management tool.

2. METHODS

Twenty-one geothermal sites were sampled for soil macro-fauna between 3rd December and 7th December 2012 (Figure 1). A total of 105 samples were assessed; five samples at each site; each consisting of a single spade divot (15 cm x 15 cm x 15 cm depth) from which the litter characteristics and soil profile were described, and soil macro-fauna were recorded. A soil temperature recording was also taken at the base of each divot. A GPS position was recorded at each location site. An assessment of

invertebrate species present in canopy foliage at each sample site was also undertaken by beating canopy foliage above a 40 cm diameter circular tray for 30 seconds and identifying all the species that fell into the tray.

Sites were selected based on the presence of representative flora associated with geothermal features, following the classification of vegetation groupings recognised in Wildlands (2011). Eight vegetation classes were sampled: 1) Prostrate kanuka/mingimingi-manuka scrub, 2) Prostrate kanuka/mingimingi scrub, 3) Prostrate kanuka shrubland, 4) Kanuka/mingimingi-manuka forest, 5) Manuka/mingimingi scrub, 6) Manuka shrubland, 7) Whauwhaupaku-kanuka/mingimingi scrub, 8) Mingimingi-kanuka-manuka-karamu/bracken scrub. The vegetation and habitat quality was evaluated at each site against a ranking classification (developed for the purposes of this study) that offered a comparison between sample sites as to the nature and amount of human-induced disturbance (either direct or indirect) to which the site had been subjected (Table 1).

Figure 1: locations of the study sites within the Taupo Volcanic Zone (Google Earth imagery).

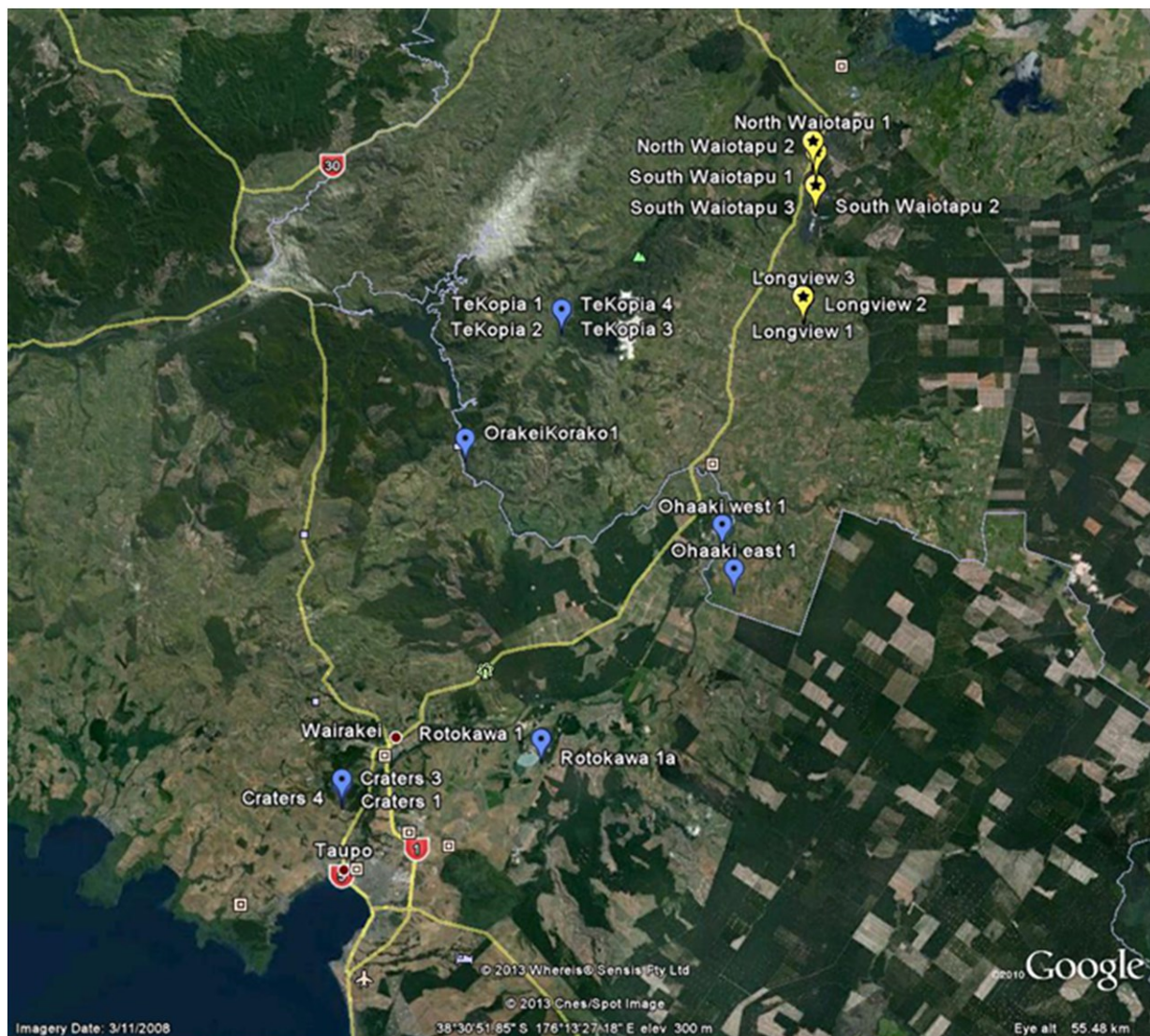


Table 1: Sample site quality ranking

| Quality ranking | Description |
|-----------------|--|
| 5 | Site undisturbed (no animal tracks or signs of trampling or browse), no weedy species present, landscape unmodified, site legally protected as park or reserve land. |
| 4 | Site relatively undisturbed (few or no animal tracks or signs of trampling or browse), few or no weedy species present, landscape unmodified, site legally protected as park or reserve land |
| 3 | Some animal disturbance evident (browse/tracking), weedy species present but not dominant, site legally protected as park or reserve land. |
| 2 | Animal disturbance evident but not heavy, landscape modified, weedy species present but not dominant, site not legally protected. |
| 1 | Signs of obvious disturbance (animal tracks, browse), weedy species prominent, highly modified landscape, site not legally protected. |

3. RESULTS

Table 2: Site locations, characteristics and quality rating (refer to Table 3 for ranking criteria)

| Site No | Latitude | Longitude | Positional Accuracy | Alt. (m) | Vegetation type | Site Quality |
|--------------------------|---------------|----------------|---------------------|----------|---|--------------|
| 1 North Waiotapu 1 | 38° 20' 31S | 176° 22' 13E | ± 5 m | 311 | Kanuka/mingimingi-manuka forest | 4 |
| 2 North Waiotapu 2 | 38° 20' 12S | 176° 22' 06E | ± 5 m | 386 | Prostrate kanuka/mingimingi scrub | 3 |
| 3 South Waiotapu 1 | 38° 21' 434S | 176° 22' 152E | ± 5 m | 335 | Prostrate kanuka/mingimingi scrub | 4 |
| 4 South Waiotapu 2 | 38° 21' 479S | 176° 22' 183E | ± 5 m | 328 | Prostrate kanuka/mingimingi scrub. | 4 |
| 5 South Waiotapu 3 | 38° 21' 510S | 176° 22' 193E | ± 5 m | 354 | Prostrate kanuka/mingimingi scrub. | 4 |
| 6 Longview Road 1 | 38° 24' 845S | 176° 21' 726E | ± 5 m | 307 | Manuka/mingimingi scrub | 4 |
| 7 Longview Road 2 | 38° 24' 50S | 176° 21' 46E | ± 5 m | 281 | manuka shrubland | 5 |
| 8 Longview Road 3 | 38° 24' 50S | 176° 21' 46E | ± 5 m | 284 | Mingimingi/manuka shrubland | 4 |
| 9 Te Kopia 1 | 38° 24' 619S | 176° 12' 556E | ± 5 m | 410 | Prostrate kanuka/mingimingi scrub | 4 |
| 10 Te Kopia 2 | 38° 24' 634S | 176° 12' 567E | ± 5 m | 418 | Kanuka/mingimingi-manuka scrub | 4 |
| 11 Te Kopia 3 | 38° 24' 634S | 176° 12' 577E | ± 6 m | 423 | Prostrate kanuka shrubland | 4 |
| 12 Te Kopia 4 | 38° 24' 625S | 176° 12' 562E | ± 6 m | 414 | Prostrate kanuka shrubland | 3 |
| 13 Orakei-Korako | 38° 28' 444S | 176° 08' 904E | ± 6 m | 295 | Prostrate kanuka-mingimingi scrub | 3 |
| 14 Ohaaki East | 38° 32' 365S | 176° 19' 111E | ± 5 m | 321 | Prostrate kanuka shrubland | 3 |
| 15 Ohaaki West | 38° 31' 042S | 176° 18' 659E | ± 5 m | 306 | Manuka shrubland | 2 |
| 16 Rotokawa 1 | 38° 37' 450S | 176° 11' 795E | ± 5 m | 332 | Mingimingi-manuka-prostrate kanuka scrub | 2 |
| 17 Rotokawa 2 | 38° 37' 30"S | 176° 11' 53"E | ± 5 m | 335 | Prostrate kanuka shrubland | |
| 18 Craters of the Moon 1 | 38° 38' 717"S | 176° 04' 190"E | ± 5 m | 451 | Mingimingi-kanuka-manuka-karamu/bracken scrub | 4 |
| 19 Craters of the Moon 2 | 38° 33' 781"S | 176° 04' 197"E | ± 5 m | 448 | Prostrate kanuka shrubland | 4 |
| 20 Craters of the Moon 3 | 38° 38' 751"S | 176° 04' 170"E | ± 5 m | 451 | Whauwhaupaku-kanuka/mingimingi scrub | 4 |
| 21 Craters of the Moon 4 | 38° 38' 624"S | 176° 04' 178"E | ± 5 m | 470 | Whauwhaupaku-kanuka/mingimingi scrub | 4 |

Table 3: Results summary including soil temperature mean (n=5) and range at 15cm depth, invertebrate macro-fauna in the foliar canopy, ground surface, litter or root mat (including mycorrhizal fungi), and within a 15 cm soil profile sample. Key to species codes is given below the table.

| Sample site (WRC Site code) | Mean Temp (°C) (range) | canopy | surface | litter/ root mat | soil |
|-----------------------------|------------------------|--------|---------|------------------|--------|
| North Waiotapu 1 (WTV03) | 27.5 (27.0 – 28.6) | 0 | A | MF, Pa | MF |
| North Waiotapu 2 (WTV03) | 24.7 (23.6 – 25.1) | 0 | 0 | RLM | 0 |
| South Waiotapu 1 (WTV05) | 34.9 (33.8 – 36.4) | 0 | A | MF | 0 |
| South Waiotapu 2 (WTV05) | 26.7 (24.0 – 30.9) | NB | A | MF(2) | NB |
| South Waiotapu 3 (WTV05) | 23.1 (22.9 – 23.3) | 0 | 0 | MBa, Cp, Cl | Cp, Cl |

| Sample site (WRC Site code) | Mean Temp (°C) (range) | canopy | surface | litter/ root mat | soil |
|--------------------------------|---------------------------|--|---------|---------------------------------------|-----------------|
| Longview 1 (RPV01) | 22.1 (20.8 – 22.8) | 0 | 0 | RLM,NB(3) | 0 |
| Longview 2 (RPV01) | 22.9 (22.5 – 23.5) | BB | BB | 0 | SM |
| Longview 3 (RPV01) | 24.4 (23.0 – 26.3) | 0 | 0 | MF (4),CBL | BB,MF(4), BB |
| Te Kopia 1 (TKV01) | 35.7 (33.8 – 37.0) | 0 | 0 | MBa,MF(3),BB | MF(3) |
| Te Kopia 2 (TKV01) | 33.6 (29.7 – 37.8) | MBa | 0 | BB, egg mass, MBa(2),MF(2),B B, | 0 |
| Te Kopia 3 (TKV01) | 35.6 (31.7 – 43.6) | 0 | 0 | BB(2),MBa(2), | 0 |
| Te Kopia 4 (TKV01) | 39.1 (33.1 – 45.7) | MBa,MBa | 0 | MBa(2) | 0 |
| Orakei Korako (OKV03) | 32.1 (26.7 – 36.7) | MBa | 0 | CBa,MF(2),BB,M F,S | 0 |
| Ohaaki East (OHV02) | 43.4 (38.7 – 48.9) | 0 | 0 | MF(3), MBa,T | 0 |
| Ohaaki West (OHV01) | 24.1 (22.3 – 25.7) | MBa | 0 | MBI,MBa,MBI, egg mass | 0 |
| Rotokawa 1 (RKV02) | 18.5 (17.3 – 19.3) | BB,MBa,BB,B B,MBa,NB,BB, MBa BUB, HB | GG, P | GG,MBI,Ba | 0 |
| Rotokawa 2 (RKV02) | 30.4 (23.2 – 37.5) | BB, BB,MBa, BB, BB | 0 | MF(5) ,GG | MBp |
| Craters 1 (WKV10) | 18.5 (17.7 – 18.9) | MBa,MBa | 0 | MF(3),MBa | 0 |
| Craters 2 (WKV10) | 33.8 (28.7 – 34.6) | MBa,MBa | 0 | 0 | 0 |
| Craters 3 (WKV10) | 18.4 (17.8 – 19.5) | 0 | 0 | BB,MBa,MF | Cl |
| Craters 4 (WKV10) | 16.1 (15.2 – 17.5) | 0 | NB | MF | MBa |

Key to species codes in Table 3:

| | | | |
|-----|---|-----|--|
| A | ants (Family: Formicidae) | MBa | manuka beetle adult (<i>Pyronota</i> sp.) |
| BUB | bumble bee (<i>Bombus</i> sp.) | MBI | manuka beetle larva (<i>Pyronota</i> sp.) |
| HB | honey bee (<i>Apis mellifera</i>) | MBp | manuka beetle pupa (<i>Pyronota</i> sp.) |
| NB | native bees (<i>Leioproctus</i> sp.) | Pa | porina adult (<i>Wiseana</i> sp.) |
| CBa | click beetle - adult (<i>Conoderus exsul</i>) | Pl | porina larva (<i>Wiseana</i> sp.) |
| CBI | click beetle - larva (<i>Conoderus exsul</i>) | MF | mycorrhizal fungus (<i>Pisolithus</i> sp.) |
| Cp | cicada - pupa (<i>Notosalta</i> sp.) | RLM | red-legged mite (<i>Halotydeus destructor</i>) |
| GG | grass grub (<i>Costelytra zealandica</i>) | SM | soil mite (Sub Order: Oribatidae) |
| Cl | cicada - larva (<i>Notosalta</i> sp.) | BB | bronze beetle (<i>Eucolaspis</i> sp.) |
| | | T | thrips (<i>Thysanoptera</i>) |

3.1 Waiotapu Geothermal Field

3.1.1 SITE 1: North Waiotapu 1 - Tourist Loop

Quality: Few weeds present and little/no site disturbance evident

Canopy: Kanuka (*Kunzea ericoides*) dominant (up to 7 m tall) with occasional tall mingimingi (*Leucopogon fasciculatus*), sparse manuka (*Leptospermum scoparium*) and prostrate kanuka (*Kunzea ericoides* var. *microflora*). Kanuka and manuka both flowering profusely at time of visit.

Understorey: Mainly kanuka with occasional mingimingi, water fern (*Histiopteris incisa*) and turutu (*Dianella nigra*).

Ground cover (0- 50 cm): Dense litter (mainly leaves and dead branches of kanuka) with seedlings/small shrubs of mingimingi, turutu, sickle spleenwort (*Asplenium polydon*), and hanging spleenwort (*Asplenium flaccidum*). Litter layer is approximately 10 cm deep (comprising predominantly kanuka and wood fragments). The main litter layer is dry and variable and often “perched” with gaps beneath the layer. Signs of mud splatter present in the litter.

General description of sample area: Located approximately 20 m south of active mud pools. Small active vents scattered throughout the site. Samples were positioned at random 5 m spacing approximately 8 m from (and parallel to) a mud feature. If a perched litter layer was present, the sample divot was taken beneath it in order to sample a full soil profile.

3.1.2 SITE 2: North Waiotapu 2: Berry’s Farm (Scenic Reserve - Department of Conservation)

Quality: Some animal disturbance evident; mainly tracking (pigs). Very few weeds present. Site fenced and otherwise relatively undisturbed

Canopy: Very dense cover of prostrate kanuka (maximum height c. 4 m) and occasional mingimingi. *Trentepohlia* alga obvious on tree branches. Kanuka in flower at the time of visit.

Understorey: Prostrate kanuka, mingimingi and dead branches.

Ground cover (0 – 50 cm): Dense dry litter (mainly from prostrate kanuka/mingimingi). Seedlings of prostrate kanuka present along with mosses and bracken (*Pteridium esculentum*), some turutu, foxglove (*Digitalis purpurea*) and very occasional fivefinger (*Pseudopanax arboreus*). High litter levels indicative of very poor soil fauna.

General description of sample area: Samples were collected approximately 20 m distant from an active geothermal feature (a small lake with active mud pools) and 30 m from the edge of pine forest/tall scrub to the east of the site. A very moist environment due to steam from the lake.

3.1.3 SITE 3: South Waiotapu 1

Quality: Located within the park reserve; well protected, no sign of animal disturbance, tourist tracks nearby. Few weeds.

Canopy: An even mix of prostrate kanuka and mingimingi approximately 1 - 2 m tall. Very dense growth branching to near ground level.

Understorey: Not distinct – layer composed mainly of canopy tree branches.

Ground cover (0 – 50 cm) Very sparse cover of *Cladonia* lichens and mosses (*Campylopus* sp.), some *Trentepohlia* alga in amongst lower and fallen branches.

General description of sample area: Site bounded by bare soil field on both sides. Prostrate kanuka in flower at the time of visit, but no bees observed (likely soil is too hot to burrow here).

3.1.4 SITE 4: South Waiotapu 2

Quality: Protected site, no animal disturbance or weeds evident. Tourist tracks nearby.

Canopy: Low cover of prostrate kanuka and mingimingi with very occasional monoao (*Dracophyllum subulatum*). Canopy height between 1.5 – 2 m. Prostrate kanuka fully in flower at time of visit.

Understorey: Not distinct – layer composed mainly of canopy tree branches.

Ground cover (0 – 50 cm): Sparse cover of lichens and mosses where the canopy is fairly open (also in and around the bases of shrubs). Ground cover is otherwise absent – mainly bare sinter cobbles on the surface.

General description of sample area: Site is approximately 5 m distant from a public walking track and around 10 m distant from an active feature. Sampling line follows a small ridge, with ground temperature decreasing in the uphill direction.

3.1.5 SITE 5: South Waiotapu 3

Quality: Some disturbance evident (from nearby track and maintenance work); no weeds present

Canopy: Tall mingimingi and prostrate kanuka (up to 4 -5 m tall)

Understorey: Shrubby mingimingi and kanuka saplings with abundant dead fallen branches/stems.

Ground cover (0 – 50 cm): Extensive patches of lichens, mosses and liverworts (very dry). Scattered individuals of turutu and patches of bracken. Abundant *Trentepohlia* on branches.

General description of sample area: The sample area was located within 10 m of large lake/spring and next to a tourist walking track. Vegetation cover fairly open and around 4-5 m tall.

3.2 Reporoa Geothermal Field

3.2.1 Site 6: Longview Road 1

Quality: Natural disturbance on site due to active feature. No weeds or animal disturbance observed. Entire site well protected, but under threat from perimeter drainage

Canopy: Very dense manuka-mingimingi; approximately 3 m tall. *Trentepohlia* alga abundant on lower branches.

Understorey: Not distinct; some bracken present, but mainly consisting of branches and dense growth of canopy manuka and mingimingi.

Ground cover (0 – 50 cm): Lichens (*Cladonia* spp.) present on mounds of pumice.

General description of sample area: Sample sites located in an area of low dense scrub on the eastern side of a small lake at the south end of the reserve (Figure), approximately 10 m from the perimeter drain. The area is active with bare soil-field and pools

close to the sampling site. Sampling line was along the slightly raised vegetated margin of the lake/soil field. Manuka was in full flower at the time of this visit and native bees were prolific – abundant presence over all the plants. *Trentepohlia* alga abundant on lower branches of the canopy trees.

3.2.2 SITE 7: Longview Road 2

Quality: No signs of animal disturbance, no tracking, few weeds. Some natural disturbance from nearby active features.

Canopy: Manuka dominant with shrubs/small trees ranging from 3 to 6 m tall. Edge trees estimated at <10 yrs old.

Understorey: Dense manuka; mostly branching of canopy trees.

Ground cover (0 – 50 cm): Light cover of manuka litter with patchy *Cladonia* lichens and mosses..

General description of sample area: Sampling sites located approximately 5 m west of the reserve perimeter drain. Flat topography. Bare soil field approximately 3 m distant in a south-westerly direction.

3.2.3 SITE 8: Longview Road 3

Quality: Stable site, with little to no obvious influence from exotic species (although deer are possibly present within the area).

Canopy: Dense low canopy approximately 0.5 to 1.5 m tall, dominated by mingimingi. Some taller manuka scattered throughout.

Understorey: Not distinct – high density of branches to ground level

Ground cover (0 – 50 cm): Sparse – mainly litter

General description of sample area: Sample site was immediately adjacent to a bare soil-field in which there are a couple of deep active vents. *Trentepohlia* alga abundant on lower branches.

3.3 Te Kopia Geothermal Field

3.3.1 SITE 9: Te Kopia 1

Quality: Site protected and relatively intact, but deer tracking extensive in places

Canopy: Dense cover of prostrate kanuka 1-2 m tall. Abundant lichen growth on shrubs (moist site with a lot of steam from active features). Quite a bit of standing-dead debris. Some mingimingi in canopy. Dwarf mistletoe (*Korthalsella salicornioides*) present

Understorey: Underlayer mainly prostrate kanuka, with turutu, leather-leaf fern (*Pyrrosia elaeagnifolia*), and mingimingi.

Ground cover (0 – 50 cm): Abundant mosses, liverworts and lichens.

General description of sample area: Sample sites were all located at the foot of a steep scarp. Samples were taken along each transect in the direction from the edge nearest farmland towards the scarp (generally eastward). Prostrate kanuka in full flower - no bees observed in sample area.

3.3.2 SITE 10: Te Kopia 2

Quality: Site protected and relatively intact, but deer tracking extensive in places

Canopy: Variable, ranging from completely closed canopy to open patches. Canopy dominated by tall kanuka (4-5 m) with mixed with mingimingi, manuka and mapou (*Myrsine australis*).

Understorey: Fairly open dominated by kanuka, and an even mix of mingimingi, mapou, manuka and prickly mingimingi.

Ground cover (0 – 50 cm): Dense cover of mosses/liverworts, ferns (*Asplenium polyodon*, *Pyrrosia elaeagnifolia*), turutu and seedlings of canopy species. Localised steaming vents nearby with tangle fern (*Dicranopteris linearis* var. *linearis*) growing in the steam zone.

General description of sample area: Sample sites were all located at the foot of a steep scarp. Samples were taken along each transect in the direction from the edge nearest farmland towards the scarp (generally eastward). Prostrate kanuka in full flower. Native bees scarce, but abundant adult manuka beetles (*Pyronota* sp.) were present in the kanuka. Deer sign present.

3.3.3 SITE 11: Te Kopia 3

Quality: Site protected and relatively intact, but deer tracking extensive in places

Canopy: Low prostrate kanuka (height approximately 50 cm-1 m) interspersed with occasional mingimingi.

Understorey: Not well defined - mainly branches and debris of the canopy species.

Ground cover (0 – 50 cm): Variable cover of mosses and lichens.

General description of sample area: Site is located approximately 40 m distant from a hot lake. Prostrate kanuka dominates the immediate area of around 0.5ha. The dense vegetation cover is interspersed by bare soil field and ephemeral flow paths. *Trentepohlia* covers low branches nearest ground. Manuka beetle adults abundant in the canopy. Deer tracks present and there are many obvious pathways through low scrub and soil field.

3.4 SITE 12: Te Kopia 4

3.5 Orakeikorako Geothermal Field

3.5.1 SITE 13: Orakei-Korako

Quality: Site protected, but modified (tourist track construction and maintenance, weeds present)

Canopy: Prostrate kanuka approximately up to 4 m tall with scattered mingimingi

Understorey: Diverse mixture of prostrate kanuka, mingimingi, and fivefinger

Ground cover (0 – 50 cm): Tangle fern, turuturu, arching clubmoss (*Lycopodiella cernua*), whisk fern (*Psilotum nudum*), mosses (*Campylopus* sp.) and lichens (*Cladonia* spp.). Leaf litter and fallen branches prominent.

General description of sample area: Site located alongside a well-formed tourist track. Presence of buried topsoil indicates site has been subject to disturbance in the near past (localised geothermal activity or possibly also alteration during construction of track).

3.6 Ohaaki Geothermal Field

3.6.1 SITE 14: Ohaaki East 1

Quality: Site is infested with weeds including *Pinus* spp. (pine), *Cytisus scoparius* (Scotch broom) and introduced grasses and has had a history of mechanical disturbance.

Vegetation type: Prostrate kanuka shrubland

Canopy: Short prostrate kanuka (average height around 0.5 m). Vegetation cover very dense in the area sampled.

Understorey: Undefined due to low height of canopy – dense branch cover to ground level.

Ground cover (0 – 50 cm): Mosses (mainly *Campylopus* sp.) abundant within canopy gaps and open edges. *Trentepohlia* alga present on low branches throughout.

General description of sample area: Site is on gently sloping ground with prostrate kanuka and mosses dominating the cover and patches of raw soil field throughout. Active features are nearby (within 10 m of the sample site). Prostrate kanuka was in full flower at the time of visit and abundant native bees and honey bees were working the flowers. Manuka beetle adults were also abundant in the vegetation.

3.7 SITE 15: Ohaaki West

Quality: Very degraded site - many weeds present, tracks (vehicle) and clearance areas and modified drainage (channel). Signs of pest animals (rabbit).

Vegetation type: Manuka shrubland

Canopy: Open canopy of manuka (3-4 m tall) with scattered prickly mingimingi (*Leptecophylla juniperina* subsp. *juniperina*), maritime pine (*Pinus pinaster*), pampas (*Cortaderia selloana*) and Spanish heath (*Erica lusitanica*).

Understorey: Manuka, prickly mingimingi, blackberry (*Rubus fruticosus* agg.), pampas, *Cotoneaster glaucophyllus*, Spanish heath and maritime pine

Ground cover (0 – 50 cm): Seedlings of manuka, prickly mingimingi, Spanish heath and Cotoneaster. Sundew (*Drosera auriculata*) also abundant with mosses (*Campylopus* sp.) and lichens (*Cladonia* sp., *Cladina leptoclada*).

General description of sample area: The sample area sits on an extensive sinter terrace near (within 30 m) an active boiling pool. The site supports a high density of weed species and has been subject to extensive modification in recent times (tracks, vegetation clearance, hydrological changes). Manuka (the dominant native species here) was in flower at the time of the site visit. Adult manuka beetle were abundant. Outlet of geothermal spring: pH 8.7, Temperature 60°C.

3.8 Rotokawa Geothermal Field

3.8.1 SITE 16: Rotokawa 1

Quality: Extensively modified with vehicle tracks/bulldozed areas, vegetation clearance and a high proportion of weedy species present.

Canopy: Mingimingi, manuka and prostrate kanuka mix up to approximately 4 m tall. Cover varies between 50 – 100%.

Understorey: Dense cover of manuka, prostrate kanuka and snowberry (*Gaultheria antipoda*) growing in and around piles of pine slash.

Ground cover (0 – 50 cm): Pine slash abundant. Live plant component includes snowberry, mingimingi/manuka/prostrate kanuka seedlings, bracken, prickly mingimingi, turutu, lichens (*Cladonia* sp., *Cladia aggregata*) and mosses (*Campylopus* sp.)

General description of sample area: Patches of dense regrowth - low vegetation occur in amongst extensive areas of bare soil field (these being either cleared or naturally bare). Felled pine debris is present throughout the area (pines have been targeted in recent weed control operations). Indigenous vegetation is in the process of re-establishing. Bronze beetle (*Eucolaspis* sp.) and manuka beetle were both abundant in the manuka.

3.8.2 SITE 17: Rotokawa 2

Quality:

Canopy: Prostrate kanuka of varying height (30 cm – 1 m) dominates. Mingimingi and monoao (*Dracophyllum subulatum*) present but uncommon in the immediate area.

Understorey: Not well defined – similar composition as the low canopy.

Ground cover (0 – 50 cm): Variable cover of mosses (*Campylopus* sp.) and lichens (*Cladonia* sp.)

General description of sample area: Prostrate kanuka dominates the low canopy. Cover is variable with patches of bare soil occurring throughout. The site is located within 10 m of an active feature and is part of an area that has been extensively modified in recent times (tracks, re-contouring and vegetation clearance). Bronze beetle and manuka beetle were both abundant in the prostrate kanuka on the day of the site visit.

3.9 Wairakei Geothermal Field

3.9.1 SITE 18: Craters of the Moon 1

Quality: Extensive tracking (old and current) throughout, some weed issues in places (wilding pines, pampas, broom, buffalo grass). Pest animals present (possum, hares, rabbits). Entire area is vulnerable to changes driven by management of the Wairakei geothermal power plants.

Canopy: Dense canopy of kanuka, mingimingi and karamu (*Coprosma robusta*) mix approximately 2 – 3 m in height. Montpellier broom (*Genista monspessulana*) also present.

Understorey: Similar composition as the canopy.

Ground cover (0 – 50 cm): Abundant dead branches covered with *Usnea* lichens. Otherwise sparse cover of canopy species seedlings with bracken and Spanish heath. Hanging spleenwort (*Asplenium flaccidum*) and onion orchid (*Microtis uniflora*) also present.

General description of sample area: Site is located near the main entrance track to the reserve but otherwise is relatively undisturbed. Some weedy species present.

3.9.2 SITE 19: Craters of the Moon 2

Quality: Extensive tracking (old and current) throughout, some weed issues in places (buffalo grass). Pest animals present (possum, hares, rabbits). Entire area is vulnerable to changes driven by management of the Wairakei geothermal power plants.

Canopy: Low prostrate kanuka 30-50 cm tall.

Understorey: Indistinct – mainly branches of prostrate kanuka.

Ground cover (0 – 50 cm): Patchy *Campylopus capillaceus* moss. Occasional patches of lichens (*Cladina leptoclada*, *Cladonia* spp.) and arching clubmoss.

General description of sample area: Dense low vegetation on a flat/ gently sloping site. Active features and patches of bare soil scattered throughout. Tourist tracks confined to a nearby boardwalk.

3.9.3 SITE 20: Craters of the Moon 3

Quality: Extensive tracking (old and current) throughout, some weed issues in places (wilding pines, pampas, broom, buffalo grass). Pest animals present (possum, hares, rabbits). Entire area is vulnerable to changes driven by management of the Wairakei geothermal power plants.

Canopy: Dense mix of 3-5 m tall five-finger/Whauwhaupaku (*Pseudopanax arboreus*), mingimingi and kanuka.

Understorey: Diverse mixture including five-finger, mingimingi and kanuka saplings with prickly mingimingi, karamu, mapou and bracken also present.

Ground cover (0 – 50 cm): Seedlings of canopy and understorey species with a mix of ferns (bracken, hound's tongue, spleenwort) and inkberry/turuturu.

General description of sample area: An island of taller vegetation between areas of prostrate kanuka shrubland. Tourist tracks pass close by site. Old (cut) pine tree stumps present within the site. Blackberry prominent.

3.9.4 SITE 21: Craters of the Moon 4

Quality: Extensive tracking (old and current) throughout, some weed issues in places (wilding pines, broom,). Pest animals present (possum, hares, rabbits). Entire area is vulnerable to changes driven by management of the Wairakei geothermal power plants.

Canopy: Dense mix of five-finger, mingimingi and kanuka

Understorey: Dense mix of canopy species with Montpelier broom, karamu, prickly mingimingi, bracken and blackberry.

Ground cover (0 – 50 cm): Abundant litter and branches with a variety of lichens (*Usnea*, *Parmelia* sp., *Cladina leptoclada*), ferns (bracken, hanging spleenwort, tangle ferns - *Dicranopteris linearis* and *Gleichenia dicarpa*).

General description of sample area: Located on a steep slope uphill from tourist tracks. Some active features nearby and evidence of previously active areas. Hillslope area has many weeds present.

4. DISCUSSION

The vegetation types chosen for sampling were generally a good fit to the geothermal vegetation classes recognised by Wildlands (2011) and with recent work by Landcare Research (WRC report in preparation 2014) which describes sixteen vegetation associations for the Taupo Volcanic Zone. Seven vegetation types were sampled in the current study. Whilst these represent only a small proportion of the many vegetation classes recognised by Wildlands, and around one-third of those recognised by Landcare, the sampled range is well aligned with the broad structural classes of woody vegetation associated with geothermal areas in the Waikato Region. Results of the present pilot study indicate that further investigations of soil macro-fauna in a greater range of geothermal vegetation classes are warranted, specifically to help better inform management actions around maintenance of environmental services and habitat.

The five-category site-quality ranking developed for this study classifies the sites relative to disturbance (human related activity; direct and indirect), including physical disturbance to the site and the ingress of weedy plants and pest animals, with these criteria ranging from not present to active incursion. These factors may be judged from a visual inspection with little or no site disturbance required. The tool simplifies the assessment of priorities put forward by Bycroft et al. (2011).

While Bycroft et al. (2011) identifies priorities for pest control and fencing on a site-by-site basis, it does not adequately recognise the inherent fragility of the vegetation (including the root mat structure and how this might be protected), the special nature of the soils, soil processes and soil macro-fauna in each system, nor does it assess each site in the context of the landscape and land-use pressures. We do not question the role of animal pest control or the protective role of fencing, but do question whether the weed pests become a problem because the geothermal habitats are inherently fragile/susceptible to invasion, or that the weeds are so aggressive that they invade anyway. We propose that all this information be integrated within a decision tool to form a strategy for managing geothermal biodiversity, with a view to prioritising objectives that provide best value for resource investment.

While not the role of this report, the implications of planting buffers to protect fragile geothermal habitats from perturbations and improving connectivity between systems to enhance resilience raise more questions than answers. From a biodiversity manager's point of view, recognising the fragility of geothermal ecosystems and understanding the consequences of disturbance would be a first step in devising a management plan, along with commissioning research to address knowledge gaps about the role of the kanuka root mat, nutrient cycling and soil macro-fauna habitats.

Initial research could target the role and dimensions of vegetated buffers to increase the resilience of what are currently many island geothermal ecosystems. Currently adjoining areas may be pasture, exotic forestry or native vegetation. Ranking the quality of individual sites with respect to adjoining land-use could be a good start point and a project that could be scoped up based on either geo-photo analysis and/or field assessment.

This information would lead to identifying sustaining linkages between both geothermal and non-geothermal communities. Pollination is a service that comes to mind for consideration. Some sites will have to be managed for native bee habitat while others may offer opportunities for managed honeybee hives for the commercial harvest of manuka/kanuka honey. For the latter licensing might be considered to ensure hives were installed annually. Increasing farming intensity, particularly dairying, has led to broad acre use of insecticides to control pasture pests. Misuse may have severe impacts on bee populations, both native pollinators and honey bees.

A significant physical feature of the root substrate at the majority of the sites sampled was the presence of undecomposed litter within which the roots, both alive and dead, were confined in the form of a mat. In some instances this root mat was elevated above the mineral soil by 2 – 4 cm and in most instances the roots did not penetrate the mineral soil. In browntop (*Agrostis capillaris*) pasture soils a root mat usually indicates the absence of soil macro-fauna that feed on and process live and dead root material as part of a nutrient cycling process (B. Willoughby personal observation). Tropical soils developed at high temperature exhibit root mats that result from fluctuating water tables depositing Ca, Mg and Al in toxic concentrations (Kingsbury and Kellman 1997). This may be an explanation where geothermal waters reach near the soil surface. The absence of soil macro-fauna at the sites sampled in the course of this survey may be a result of toxicity and/or temperature. As earthworms are primary agents for nutrient cycling and mineral soil formation the fact that none were detected in the course of this survey begs the question as to how nutrients are cycled in geothermal soils under native vegetation. The absence of predatory insects (e.g. from the families Staphylinidae and Carabidae) and their prey (e.g. Order Collembola) in the root mat and litter is also significant, indicating that the nutrient cycling processes in soils developed over geothermal heating do not resemble what might be seen as a ‘normal’ soil process.

In considering how the flora of geothermal areas might best be managed the apparently unique ‘soil’ environment must be considered. There are processes important to the maintenance of the flora in terms of nutrient cycling that are yet to be elucidated, particularly with respect to the role of the ectomycorrhiza *Pisolithus* sp. This fungal genus has been shown as effective in improving plant growth in dry soils with high soil temperatures (Garbaye et al 1988, Marx et al 1977) and is restricted in New Zealand to geothermal areas (Moyersoen 2004). The fungi may be implicated in the ability of prostrate kanuka to survive in geothermal sites and as such a better understanding of its role and implications for re-establishing prostrate kanuka would be valuable. *Pisolithus* sp. was observed to be widespread in our (2012) survey, but no associations with land-use were undertaken as the survey was not designed to provide that detail. A better understanding of its role in nutrient uptake for kanuka in geothermal areas would be useful and could be assessed by site quality, adjacent land-use and presence. The association would be by implication but still useful from a biodiversity management point of view.

Immediate questions arise as to the supporting role of surrounding mineral soils developed under ambient rather than geothermal temperatures. Willoughby (2012) demonstrated that once removed from the influence of geothermal heating, soil macro-fauna, and one assumes the nutrient cycling processes, exhibited expected diversity.

Manuka beetle and bronze beetle adults were observed in large numbers on the foliage of manuka and kanuka at some of the sites. Eggs in the soil might be expected at this time of the year. However, despite close inspection few were detected and an absence of root pruning as evidence of the presence of the larvae was also not seen. Wing-cases (elytra) of manuka beetles and bronze beetles were noted in the root mat but these may have originated from adults that had died naturally on the soil surface. The question this elicits is where are the eggs of the beetles laid and where do the larvae develop in geothermal habitat mosaics?

The raised root mat implies a very fragile system that if disturbed may require a number of essential components for restoration. For example what might be the role of the litter in terms of propensity to break down under the geothermal conditions? Why does prostrate kanuka dominate these systems? The fact that ectomycorrhiza may play a vital role in the survival of prostrate kanuka may have implications for restoring or managing geothermal sites. In the apparent absence of mechanisms for effective nutrient cycling these sites may be more dependent on managed buffers to ensure nutrients are available to the resident plant species.

Buffers and linkages may have an important role in terms of the maintaining habitat mosaics and sustaining both the soil macro-fauna and flora. Field observations of plant death indicated that plant populations are vulnerable to ‘wandering’ areas of high soil temperatures. The presence of a suitable soil environment (temperature) to sustain insect populations is also important for pollination. This is particularly important since the introduction of the varroa mite (*Varroa destructor*) in 2000 has decimated feral honeybee colonies (Kraus 1995) that in many cases supplanted native pollinator roles in pollination of native plant species. For example beetles and native bees will forage in the areas of high soil temperatures but in the example of manuka beetle must have survivable soil temperatures to complete life cycle. In the example of native bees, which live in burrows but forage into the areas of high temperature, there must be suitable conditions (soil) to enable their survival.

5. RECOMMENDATIONS

Potential loss of ecological services such as pollination, and the significance of the absence of soil macro-fauna that act in a role as decomposers and the role of mycorrhizal fungi have been identified in this report. Measures of ecosystem resilience of geothermal systems are lacking but need to be identified in order to manage ecosystem resilience. Taking as an example the soil root mat; understanding how it is formed, what is its role in isolating root systems from high temperatures and how nutrient cycling is affected? Gaining a better understanding of the features of this system would also provide more certainty around the role of suitable buffers and linkages in sustaining ecosystem function and resilience.

For effective management better understanding of the environmental services provided by geothermal features is needed. The role of functional groups in relation to biodiversity priorities is not well understood in geothermal terrestrial ecosystems. The implication of the loss, or part loss, of functionality is currently unknown. Examples may include the role of pollinators in sustaining populations of geothermal vegetation but also in protecting the habitat of the pollinators themselves. It is recommended that functional groups be identified and prioritised at a site level.

The three areas of threats (weeds, pest animal and domestic stock) to geothermal terrestrial vegetation as defined by Bycroft et al (2011) go partway to defining system vulnerability. Weeds may be symptomatic of a system fragility/susceptibility or reflect invasion aggression. Factoring in the role of functional systems such as the health of soil macro-fauna (and micro flora) by identifying and managing risk for that functionality is essential for effective ecosystem management.

A site quality ranking tool is being developed in conjunction with the criteria set out in Bycroft (2011) to categorise geothermal sites as to vulnerability, particularly with respect to ecosystem services. Progress on this will be reported in 2015. Its purpose is to inform decision making as to the allocation of resources to preserve geothermal site biodiversity. This tool would be risk-analysis based. Using the site quality tool as a start point it is envisaged that individual sites may be comparatively evaluated as to the probability of sustainably managing biodiversity and ecological services. Inevitably the process will identify information gaps and one role of the process would be how to best address these.

Site evaluation for the purposes of biodiversity management will focus on the types and quality of vegetation present including both native and introduced species. Threats to the integrity of the geothermal ecosystem both above and below ground in the form of adjacent land-use and degree of isolation within a context of integrated landscape management would also be considered. The process is split into two stages:

5.1 Stage 1. Developing A Geothermal Site Biodiversity Management Decision Tool

Using the site ranking tool (Willoughby and Beard 2013) as the basis of a first phase decision tool, a second phase decision tool will be developed primarily based on existing resource materials. The objective is to design a decision tool to facilitate the prioritisation of management objectives that would give best value for resource investment at an individual site basis. The tool will also be designed to facilitate the identification of sustaining linkages between both geothermal and non-geothermal plant and animal communities.

Additionally the decision tool would be designed to facilitate identification of the role and dimensions of vegetated buffers to increase the resilience of what are currently many island geothermal ecosystems. Adjoining areas may be pasture, exotic forestry or native vegetation. Ranking the quality of sites with respect to adjoining land-use would be used as a start point. A decision is required as to whether a project would be scoped up based on the current geo-photo analysis (Wildlands 2011) and/or field assessment.

The structural form of the tool would employ four components: 1. Health of indigenous flora and fauna, 2. Environmental services, 3. Threats, 4. Economic opportunities.

Within these components between one and three key measurable factors would be selected as indicators to populate the tool. It is anticipated that there would be no more than three measurable components to each of the categories.

5.1.1 Health of indigenous flora and fauna:

Plant species associations and spatial information for geothermal vegetation in the Waikato region outlined in Smale & Fitzgerald (2013) and the Wildlands Consultants Ltd report (2011) would be used to devise indicative measures of the state/health of vegetated geothermal associations. The practicality of identifying key indicator indigenous plant species and/or associations for habitat health will be investigated. The practicality of leaf chemical composition (chlorophyll, nitrogen, phosphorus, potassium) of key indigenous plant species will be considered. However, the complexities of the soil environment in terms of temperature, nutrient and pH variation may make this approach impractical.

In the absence of a direct measure of community health proxy measures will be devised based on the following indicators;

- Dominance of indigenous species (plant and animal): This would take the form of a ranking of the composition of the associations within a geothermal site based on the relative presence and functionality of indigenous species.
- Presence of rare indigenous species: It is envisaged that this factor would be a subset of the above.
- Diversity of habitats: A ranking system based on the premise that the greater the diversity of habitats within a geothermal site implies greater conservation value would form the basis for this assessment.
- Recruitment potential: This ranking would be based on the potential for both the recruitment of indigenous and exotic species

5.1.2 Environmental Services

A minimum one to a maximum of three environmental services would be identified. These may be intrinsic or extrinsic or both. Intrinsic services would be confined to servicing the geothermal community.

As an example, pollination as an environmental service would be assessed. Characteristics of native geothermal vegetation may preclude all but some specific pollinator species. For flowering plants these may be either birds or insects (or both). The field programme would be designed to identify the key pollinators (from observation at the flowering of key native vegetation of New Zealand geothermal areas) and then determining as to whether there was suitable habitat for these pollinators within the prescribed geothermal area. Some sites may have to be managed for native pollinator habitat while others may offer opportunities for managed honey bee hives for the commercial harvest of manuka honey. For the latter licensing might be considered to ensure hives were installed annually. Increasing farming intensity, particularly dairying, has lead to broad acre use of insecticides to control pasture pests. Misuse may have severe impacts on bee populations, both native and honey bee.

Adult endemic beetles (*Pyronota* sp. and *Eucolaspis brunnea* (Fabricius) have been noted feeding and mating in large numbers on prostrate kanuka in geothermal areas (Willoughby and Beard 2013). These scarab species are univoltine with a soil dwelling larval stage, inviting the question as to where the larvae live. It may be accepted that the insect species and plant have co evolved, and there may be some mutual dependencies as yet unidentified. However, the future of the relationship relies on suitable soil conditions for larval survival. These conditions often do not exist within the immediate area of prostrate kanuka habitat. There is no record of the larvae of either species occurring in farmland.

Another area to be addressed is nutrient cycling, particularly with respect to the role of the ectomycorrhiza *Pisolithus* sp. It was observed to be widespread in the Willoughby & Beard (2012) survey but no associations with land-use were undertaken as our survey was not designed to provide this detail. A better understanding of its role in nutrient uptake for kanuka in geothermal areas would be useful and could be assessed by site quality, adjacent land-use and presence. The association would be by implication but still useful from a biodiversity management point of view.

5.1.3 Threats:

Threat may be categorised as intrinsic or extrinsic. A minimum of one to a maximum of three of both threat types would be identified. An example of a measurable intrinsic threat may be the nature of the geothermal heating in a geothermal area to 'wander' or move spatially over time. The pattern of geothermal heating of the soil may change influencing that nature of the native vegetation. Historical records of 'wandering' would enable a determination to be made of the extent of a managed geothermal significant natural area (GeoSNA).

A measurable extrinsic threat may be the nature of adjacent land use. This may be in the form of fertiliser runoff and/or grazing animals. Intensive livestock farming may subject a GeoSNA to fertiliser runoff. Additional nitrogen and/or phosphorus may significantly alter the chemical profile of the soil within a GeoSNA. Depending on the mode of transport buffer areas and/or interception may provide a solution. Grazing animals may pose a threat to indigenous vegetation within a GeoSNA

5.1.4 Economic opportunities:

The economic opportunities of the natural capital and ecosystem services of geothermal areas need to be studied and factored into considerations regarding funding of further work.

5.2 Stage 2: Field Testing A Geothermal Site Biodiversity Management Decision Tool

We envisage that the field testing will be designed as an indicative rather than a definitive study. That is, the depth of investigation confined to information that might populate the decision tool. As such, stage two would involve selecting a range of sites (number to be confirmed) based on key factors identified in Stage 1. These key factors would come under four aforementioned categories.

REFERENCES

- Boothroyd, I.K.G. and Browne, G.N. (2006): Invertebrates of geothermally influenced aquatic and terrestrial ecosystems: longitudinal and lateral linkages. Proceedings of the 28th New Zealand Geothermal Workshop. Auckland University, New Zealand, 212-216.
- Bycroft, C., Beadel, S., Collins, L., and Shaw, W. (2011): Priorities for pest plant control, pest animal control, and fencing at geothermal sites in the Waikato region in 2011. Waikato Regional Council Technical Report 2011/28. Hamilton, Waikato Regional Council. <http://www.waikatoregion.govt.nz/tr201128>
- Garbaye, J., Delwaulle, J.C., and Diagana, D. (1988): Growth response of Eucalyptus in the Congo to ectomycorrhizal inoculation. Forest Ecology Management 24 pp 151-157
- Kingsbury, N. and Kellman, M. (1997): Root mat depths and surface soil chemistry in Southwestern Venezuela. Journal of Tropical Ecology 15 pp. 475-479
- Kraus, B., Page, R.E. (1995): Effect of *Varroa jacobsoni* (Mesostigmata: Varroidae) on Feral *Apis mellifera* (Hymenoptera: Apidae) in California. Environmental Entomology Vol. 4, No. 6 pp 1473-1480
- Marx, D.H., Bryan, W.C. and Cordell, C.E. (1977): Survival and growth of pine seedlings with *Pisolithus* ectomycorrhizae after two years on reforestation sites in North Carolina and Florida. Forestry Science 16 pp. 363-373
- Moyersoen, B. and Beever, R.E. (2004): Abundance and characteristics of *Pisolithus* ectomycorrhizas in New Zealand geothermal areas. Mycologia, 96 (6) pp 1225-1232
- Smale, M.C. and Fitzgerald, N.B. 2013 Vegetation types of the Taupo Volcanic Zone. Waikato Regional Council Technical Report (in press).
- Thompson GEK 1965. Regional ground temperature survey in the Taupo-Reporoa depression. New Zealand Journal of Geology and Geophysics. 8(3):527-29.
- Wildland Consultants Ltd (2011): Geothermal vegetation of the Waikato region - an update based on 2007 aerial photographs. Waikato Regional Council Technical Report 2011/29. Hamilton, Waikato Regional Council. <http://www.waikatoregion.govt.nz/TR201129>
- Willoughby, B. 2012 Soil macro-fauna in geothermal heated soils in the Waikato Region. Waikato Regional Council Technical Report <http://waikatoregion.govt.nz/tr201229>
- Willoughby, B. and Beard, C. 2013 Invertebrate macro-fauna in geothermal soil under native vegetation in the Waikato Region. Waikato Regional Council Technical Report <http://waikatoregion.govt.nz/tr201332>