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Vegetation of High-temperature Geothermal Areas in Iceland

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ABSTRACT

The high-temperature geothermal areas in Iceland are all within the volcanic zone that crosses the country from southwest to northeast. The areas vary in size, elevation, climatic conditions and activity of the geothermal systems. Geothermal activity is common in Iceland; however the associated unique environment at the surface is usually small and occurs in patches. The demand for utilization of the areas for energy extraction is increasing as is also the demand for recreation and nature conservation. Several high-temperature geothermal areas still remain in pristine condition but care has to be taken to preserve them.

The vegetation of high-temperature geothermal areas was studied in two separate studies during 2001-2008. Prior to these projects the flora of geothermal fields was fairly well known but a comprehensive overview was lacking. In the first study vegetation was studied in a few selected high-temperature geothermal sites to determine the distribution of vegetation in relation to physical and chemical parameters. The main objective of the second study was to investigate the flora and map the vegetation of high-temperature geothermal areas. The vegetation sampling varied slightly between the two studies but in all cases vascular plants were identified, samples of mosses and lichens were collected, soil temperature was measured at a depth of 10 cm and homogeneous vegetation types were mapped on orthophotos or satellite images. These projects were part of the Icelandic Framework Plan for the Use of Hydropower and Geothermal Energy.

The results of the studies gave the first comprehensive information about plants and vegetation in geothermal areas in Iceland, including the distribution of plant species and occurrence of protected, red listed and geothermal species within the areas. The total number of plant species, number of vascular plant species and soil organic carbon content showed a clear negative response to high soil temperature and low pH. The classification of the vegetation resulted in determination of nine vegetation types and three land types in the geothermal areas that were related to soil temperature, ground water level and geothermal features. These types were sorted in three main vegetation groups and one land type.

1. INTRODUCTION

The geothermal systems are hydrothermal, referring to the transport and circulation of water within the deep crust. Through convection hot fluid rises towards the ground surface, often accompanied by the deposition of elements. As a consequence the environment of geothermal areas is often unique and characterized by a steep gradient in soil temperature and humidity, high acidity and an unusual concentration of minerals and elements (Chiarucci et al. 2008, Burns 1997, Given 1980). These conditions affect the vegetation that can be quite different from the surroundings. Merrett and Clarkson (1999) described "geothermally" influenced terrestrial and emergent wetland vegetation as plant communities that have compositional, structural or growth rate characteristics that are influenced by the geothermal heat directly or indirectly. These conditions of geothermal areas are rare phenomena worldwide but are valued features and great attractions for tourism.

Geothermal fields are found in many parts of Iceland and are divided into high- and low-temperature geothermal fields on the basis of the maximum temperature in the uppermost 1 km (Fridleifsson 1979). In low-temperature areas the temperature is <150°C and the water is usually alkaline and has a pH>7. In contrast, the high-temperature areas have a temperature above 150°C and are characterized by acidic thermal water. There are at least 20 high-temperature areas, all within the volcanic zone that crosses the country from southwest to northeast (Ragnarsson 2013). Seven of them are already utilized for geothermal power plants and there are plans for further expansion. There are around 250 low-temperature areas, located in older rock formations that are cooler and not directly connected to the volcanic zone. Many of these areas have been disturbed by utilization.

At the end of the nineteenth century studies of geothermal vegetation in Iceland gave good information on species occupying these habitats. However, they did not give comprehensive information on vegetation composition or species distribution and published material was in general lacking (Kristjánsson and Alfredsson 1986, Steindórsson 1964, Pétursson 1958). The geothermal areas are part of the volcanic characteristics of the country and attract an increasing number of tourists, but are at the same time under increasing pressure for energy extraction. They are also valuable because of their scientific value and their unique scenery. Knowledge of the ecosystems of geothermal areas is important as it will contribute to improved decision making on their utilization and need for protection. In order to gather more comprehensive information on the flora and vegetation within high-temperature geothermal areas, two studies were established during the period 2001-2008. Study 1 was established in 2001 to demonstrate the distribution of plant species and vegetation in relation to physical and chemical parameters (e.g. soil temperature, soil pH, soil carbon and height above sea level) in selected high-temperature geothermal areas in Iceland (Elmarsdóttir et al. 2003). The main objective of study 2, started in 2005, was to identify, map and classify the vegetation of all accessible high-temperature areas (Elmarsdóttir and Vilmundardóttir 2009). These projects were established and funded by the Icelandic Framework Plan for the Use of Hydropower and Geothermal Energy (Master Plan for hydro and geothermal energy resources in Iceland 2014).

2. STUDY SITES AND METHODS

STUDY 1

The relationship of plant species and vegetation distribution with physical and chemical parameters was studied within six sampling sites located at five high-temperature geothermal areas in 2001-2002 (Figure 1). The focus of the study was on geothermal heated soils which were defined as land where the soil temperature was >15°C at 10 cm and increased with depth. Two transects were extended from a geothermal feature where soil temperature was high to a regular cool part of each site. A transect along the temperature gradient was considered complete when the soil temperature was measured at ambient level and remained constant or decreased with depth. The length of each transect varied between 40-430 m. Within each transect, 4-5 plots (10x10 m) were chosen subjectively to represent vegetation that was as homogeneous as possible within each plot but encompassed differences in vegetation composition and soil temperature found at that site. The plot number indicates the transect number (number 1 or 2) and the number of the plot (numbers 1-5). Plot numbers 1-1 and 2-1 are located next to the hottest spot or a geothermal feature. Eight subplots (33x100 cm) were placed randomly within each plot and all measurements were made within them. All vascular plant species were identified and their cover determined according to modified Braun-Blanquet cover classes (Goldsmith and Harrison 1976). The cover for mosses and lichens as groups was also estimated. The average cover and number of species were then calculated for each plot. Samples of mosses and lichens were taken within each plot for species determination. The scientific names of the vascular plants follow Kristinsson (2008).

Soil temperature was measured at two spots in each subplot at 10 cm depth. One soil sample was collected within two subplots with a soil core of 5.2 cm in diameter to a depth of 10 cm for determination of soil pH and carbon concentration. Samples were dried at room temperature and samples from each plot were combined into one composite sample before analysis. Determination of pH was performed for samples that were rewetted with deionized water to a saturated paste and measured with a glass electrode (McLean 1982). The soil carbon content was analyzed by means of a Leco–CR 12 Carbon Analyzer. To study the relationship between vegetation and other factors a locally weighed scatter plot smooth (LOESS) was applied.

STUDY 2

Seventeen high-temperature geothermal areas were studied in 2005-2008, including sites from study 1 (Figure 1, Table 1). The areas were outlined and defined with Transient-electro-magnetic measurements as well as known geothermal features, with sizes ranging from 5-270 km^2 (Árnason and Karlsdóttir 2006). Available information on geology, geothermal features, vegetation, flora and accessibility was used to locate sampling sites prior to the field work. The size and number of sampling sites depended therefore on the variation known within each geothermal area. In a few instances a sampling site was added during fieldwork, in cases where information on the area was lacking. There was a total of 40 sampling sites (1-11 within an area) and their sizes ranged from 29-1384 ha (Table 1). Within each site, homogeneous vegetation was mapped as polygons on orthophotos or satellite images, mainly on geothermal heated soil but also in its surroundings where the soil temperature was regular. Vascular plants were identified within each polygon and each species ranked in one of three classes according to their cover. Mosses and lichens were sampled within each polygon. Soil temperature was measured at 10 cm depth along the center of each polygon and measurement taken at 4-10 spots, depending on the size of the polygon. Measurements were performed in July and August. The monthly means for air temperature were obtained for the period 1961-1990 (Björnsson 2003).

The main analyses of the vegetation were carried out with ordination and classification using the PC-ORD program (McCune and Mefford 1999). The analyses were based on polygons where the soil temperature was >15°C, a total of 237 polygons and 192 vascular species. The correlation of environmental variables with the ordination axis was investigated.

Table 1: The size of geothermal areas (km^2) and sampling sites (ha) in study 2. Number, elevation, median and maximum soil temperature measured at 10 cm depth refer to the sampling sites.

Geothermal areas		Sampling sites				
Name	**Size** (km^2)	**Size** (ha)	**Number**	**Elevation** (m)	**Median** °C	**Max** °C
Brennisteinsfjöll	5	65	1	410-480	32.4	68.5
Geysir	5	40	1	100-180	29.3	69.3
Reykjanes	9	43	1	20-30	46.4	91.9
Fremrinámar	10	535	1	760-920	38.4	91.6
Gjástykki	11	53	1	480-500	27.1	56.7
Hveravellir	14	187	1	640-660	37.2	98.3
Námafjall	17	133	2	320-460	31.1	80.1
Askja	27	782	1	1060-1400	45.1	92.0
Vonarskard	29	1021	1	940-1280	21.1	95.5
Kerlingarfjöll	31	578	2	920-1180	19.6	37.9
Kverkfjöll	31	161	1	1560-1740	64.0	94.2
Svartsengi-Eldvörp	32	79	2	30-120	39.0	85.8
Krafla	46	116	3	420-660	31.4	98.0
Theistareykir	48	29	2	340-380	19.9	72.1
Krýsuvík	72	128	2	160-300	24.6	91.0
Hengill	173	139	7	180-480	35.6	99.6
Torfajökull	270	1384	11	620-1100	28.0	98.0

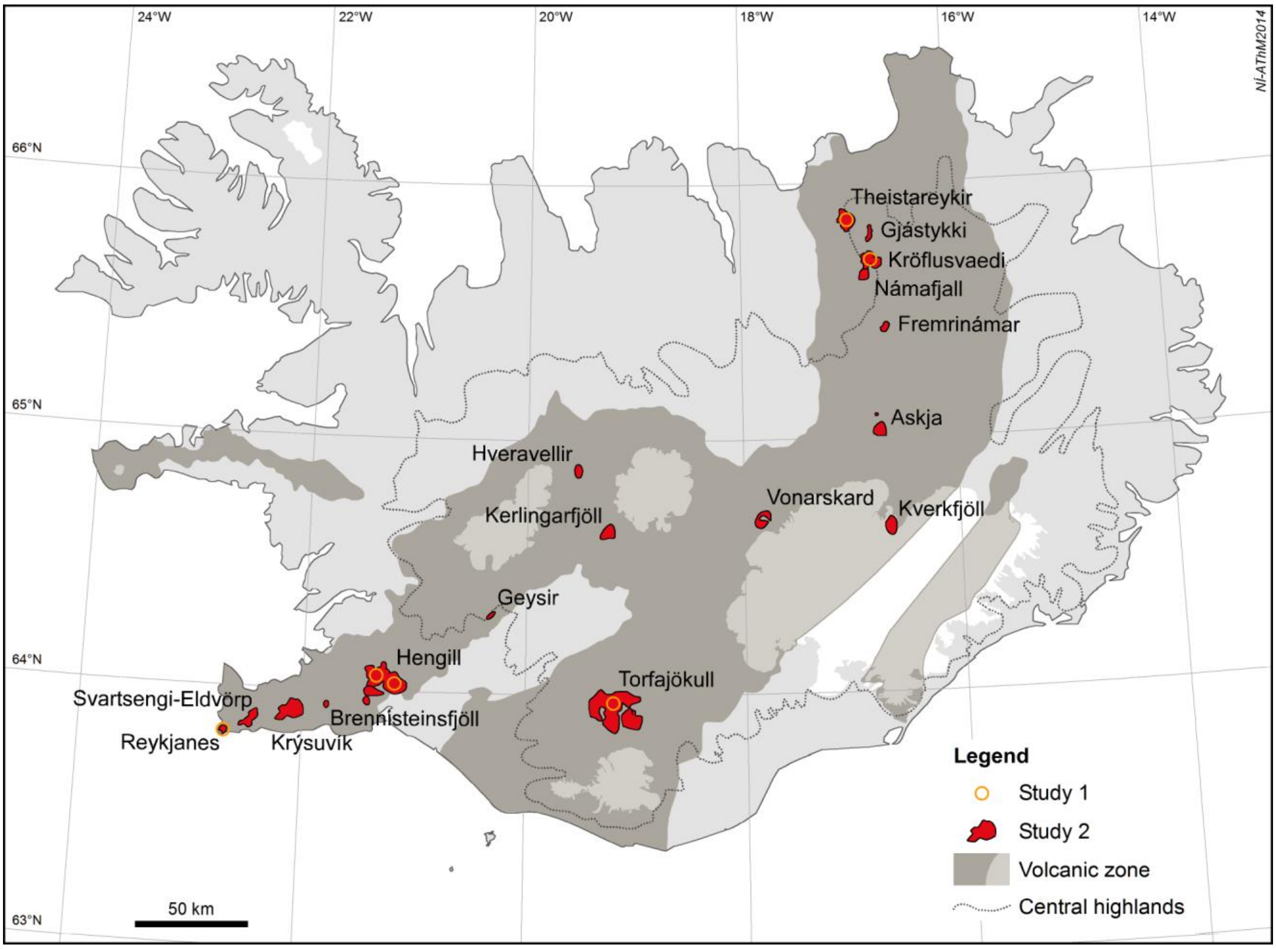


Figure 1: Vegetation was studied at six sampling sites in study 1, during 2001-2002, and seventeen high-temperature areas in study 2, during 2005-2008.

3. RESULTS

STUDY 1

Relationship between soil and vegetation

Temperature measurements on transects in 2001-2002 clearly showed the variability in temperature among sites (Figure 2). The temperature gradient varied greatly and therefore the length of each transect. Soil temperature measurements within a plot were usually similar with little variation between subplots (Figure 2). The variation was, however, more obvious where soil temperature was highest. A relationship was found between soil temperature and several of the variables measured. Both soil pH and carbon concentration decreased with an increase in soil temperature (Figure 3). The lowest pH was at Theistareykir where it was 1.9 with soil carbon 0.3% at 38.4°C soil temperature. The carbon concentration in plots with soil temperature >50°C was 0.37% (0.12-0.87%) on average.

The total cover of vegetation tended to decrease gradually as the temperature increased but plant groups responded differently (Figure 4). Vascular plants dropped in cover at around 50°C and the cover of lichens around 30°C; their cover did not exceed 25% and 10%, respectively, above that temperature. On the other hand, less change was found in the cover of mosses along the temperature gradient, though it decreased with increasing temperature. The total number of species (vascular plants, mosses and lichens) was also affected by soil temperature and it decreased as soil temperature increased (Figure 5). The total number of species varied considerably at a soil temperature below 15°C where it ranged from 16 to 59 per 100 m^2. The number of vascular species decreased with increased temperature and was less than ten species per plot at a soil temperature of >50°C. Similarly, the number of lichen species decreased with higher soil temperatures and fewer than five species were found in plots with a temperature above 30°C. A clear relationship between the number of moss species and soil temperature was not found.

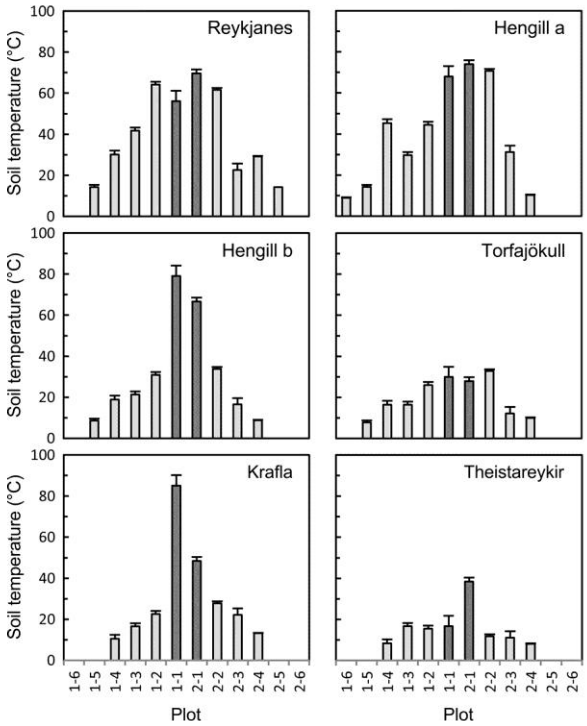


Figure 2: Average soil temperature (ºC) at 10 cm depth (+/- SE) in 10x10 m plots at six high-temperature sites studied in 2001-2002. The plots are located on transects spanning from a geothermal feature within each site (dark column) and the length of the each transect was 40-430 m.

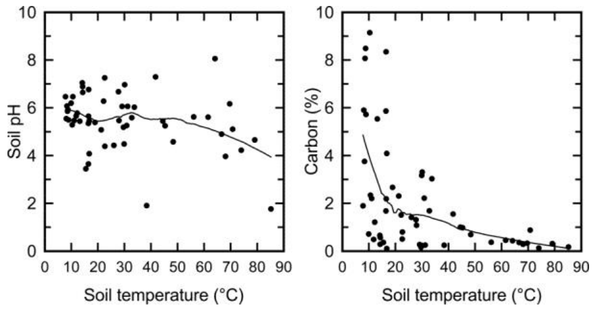


Figure 3: Soil pH and soil carbon at different soil temperatures within six high-temperature sites studied in 2001-2002. Each point represents an average of the corresponding plot and the lines indicate locally weighed scatter plot smooth.

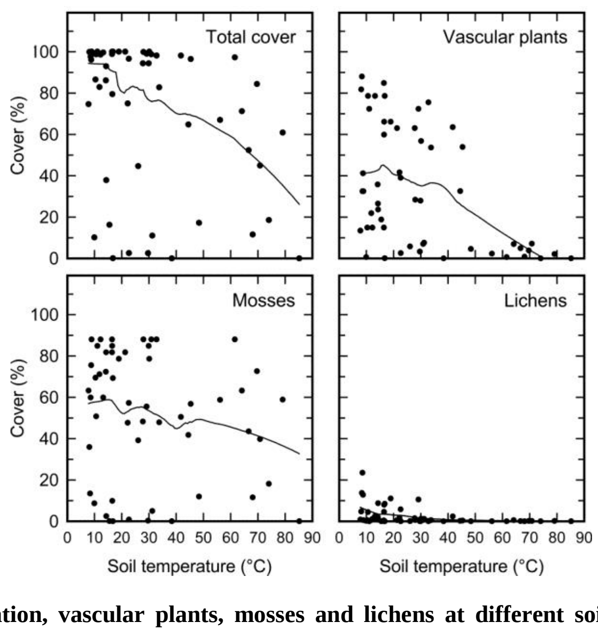


Figure 4: Total cover of vegetation, vascular plants, mosses and lichens at different soil temperatures within six high-temperature sites studied in 2001-2002. Each point represents an average from eight 0.33 m^2 subplots within each 10x10 m plot. Lines indicate locally weighed scatter plot smooth.

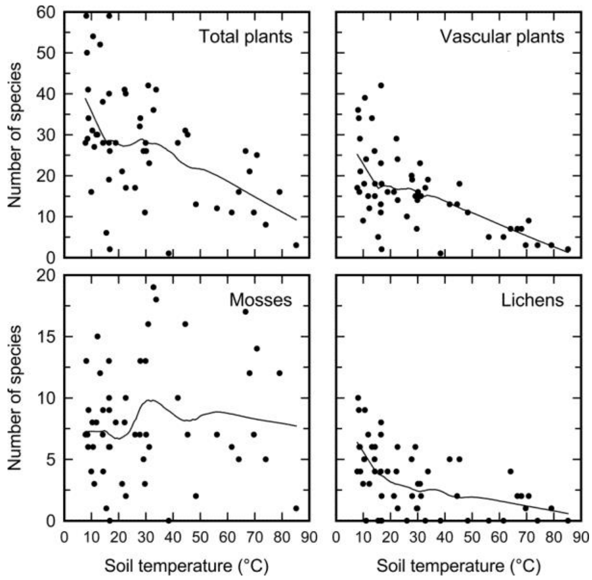


Figure 5: Total number of plant species and number of vascular species, moss species and lichen species at different soil temperatures within the six high-temperature sites studied in 2001-2002. Each point represents the number of species within each 10x10 m plot. Lines indicate locally weighed scatter plot smooth.

STUDY 2

Flora

In the survey of 2005-2008 a total of 192 vascular plant species, 209 bryophyte and 60 lichen species were recorded at seventeen high-temperature areas in Iceland where the soil temperature was 15°C and higher. The vast majority of the species are common in Iceland. Species richness was highest at Hengill, Hveravellir and Torfajökull (224-238) but lowest at Kverkfjöll where only seven moss species were found (Table 2). There was a difference among study areas in the number of red list species and geothermal species (Table 2). Most of these species were found at Hengill, Geysir and Torfajökull. Two geothermal species that are red listed vascular species were found within the high-temperature areas. *Ophioglossum azoricum* was found within twelve areas and *Veronica anagallis-aquatica* was found within four areas. Additionally, the geothermal species *Gnaphalium uliginosum* was found within four of the high-temperature areas. Eight red listed moss species were documented. One of them, *Dicranella heteromalla*, is also classified as a geothermal species and was found in two areas. The geothermal moss species *Campylopus introflexus* was found in seven areas and is defined as an invasive species in Iceland. No lichen species were found within the study areas that are classified as red listed.

Table 2. Total number of plant species, number of vascular, lichen, moss, red listed and geothermal species within the seventeen high-temperature areas studied in 2005-2008.

	Total	Vascular	Lichens	Mosses	Red listed	Geothermal
Brennisteinsfjöll	84	28	47	9	0	6
Geysir	134	79	51	4	4	7
Reykjanes	74	34	28	12	2	5
Fremrinámar	41	19	14	8	1	3
Gjástykki	81	40	31	10	2	4
Hveravellir	225	111	89	25	1	6
Námafjall	90	50	30	10	2	6
Askja	55	25	27	3	1	4
Vonarskard	101	49	46	5	1	4
Kerlingarfjöll	58	34	24	0*	0	1
Kverkfjöll	7	0	7	0	0	0
Svartsengi-Eldvörp	99	57	32	10	1	5
Krafla	155	81	55	19	1	5
Theistareykir	31	22	7	2	0	0
Krýsuvík	90	60	29	1	1	2
Hengill	238	111	113	14	6	11
Torfajökull	224	98	106	20	3	9

*No samples collected

Vegetation classification

The result of a TWINSPAN classification of 237 mapped polygons with 192 vascular plants showed that there was a difference in vegetation, mainly in relation to height above sea level. The first TWINSPAN division separated polygons of areas that lie below 800 m a.s.l. from those above 800 m a.s.l. with a few exceptions (15 polygons). The class "below 800 m" included 143 polygons from Reykjanes, Svartsengi-Eldvörp, Krýsuvík, Brennisteinsfjöll, Hengill, Geysir, Hveravellir, Námafjall, Krafla, Gjástykki and Theistareykir, whereas the class "above 800 m" included 94 polygons from Kerlingarfjöll, Vonarskard, Askja, Fremrinámar and Torfajökull. The second division reflected soil moisture in the areas and further classification of the data resulted in twelve classes that were used for defining geothermal vegetation types.

The DCA ordination revealed a distinct difference in the vegetation between the two main groups below and above 800 m a.s.l. (Figure 6). The eigenvalues for axes 1, 2 and 3 were 0.46, 0.33 and 0.20, respectively, and reflect the majority of the variability in the dataset. The first axis represents variation that is due to elevation and consequently the monthly temperature mean in January and July. Polygons that lie to the right side of the graph are from areas that are located higher above sea level and with lower annual temperature than those to the left of the graph. Precipitation shows relation along axis 2 and increases along the axis. The vegetation data show less connection with soil temperature, which, however, does decrease along axis 2. The soil temperature at 10 cm depth varied between the seventeen high-temperature areas; however, in the majority of the areas the maximum soil temperature was higher than 90°C (Table 1). There was therefore no great difference with respect to extreme soil temperature.

The results from both TWINSPAN and DCA ordination were used to define geothermal vegetation classes. Nine vegetation types were determined and three land types (Figure 7). The vegetation types were classified into three main geothermal groups (Table 3): moss heath (four vegetation types), grassland (two vegetation types) and wetland (three vegetation types). Three of the vegetation types were only found within areas that lie above 800 m a.s.l. and the other six were mainly found below 800 m a.s.l. (Figure 7). The land types were found both above and below 800 m a.s.l. Considering the soil temperature and the number of species there was a difference among the three main geothermal groups and land types (Table 3). On average the soil temperature was highest in the moss heath but considerably lower and similar within the other groups. Species composition varied among the three main groups and land types, though several species were common to all of them.

Data results and field observations were used to develop a schematic diagram to demonstrate the interaction of geothermal heat, ground water level, geothermal features and vegetation (Figure 8). On top of hills, or where ground water level is low, fumaroles and geothermal heated soils are common. The soil is transformed to exposed geothermal clay where hardly any vegetation thrives due to high soil temperature and low pH. Adjacent to it, mosses are dominant with dwarf shrubs, dicots and grasses. As the ground water level rises, the soil moisture content increases and soil temperature decreases. This environment is suitable for grassland where dicots and dwarf shrubs are common, along with grass species. Hot springs and hot creeks become prominent in the geothermal wetland where the ground water level intersects the surface.

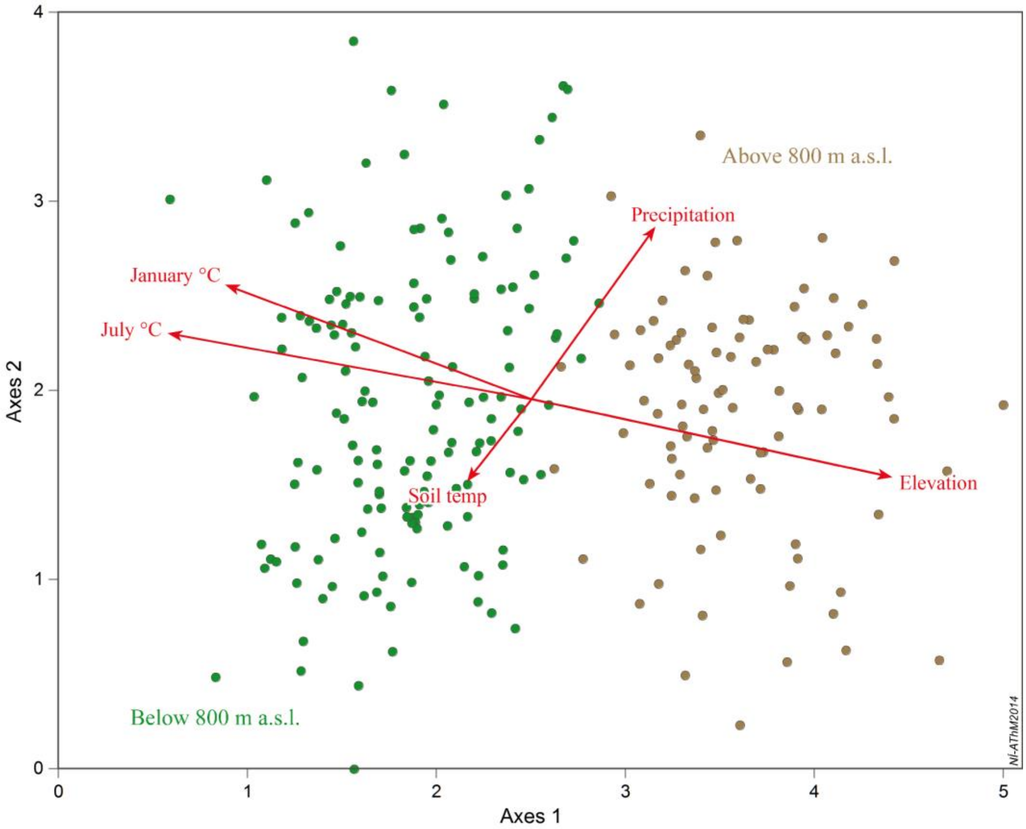


Figure 6. DCA ordination results based on polygons where soil temperature was >15°C, studied in 2005-2008. Arrows indicate direction of main change for each variable and their lengths indicate strength of the correlation.

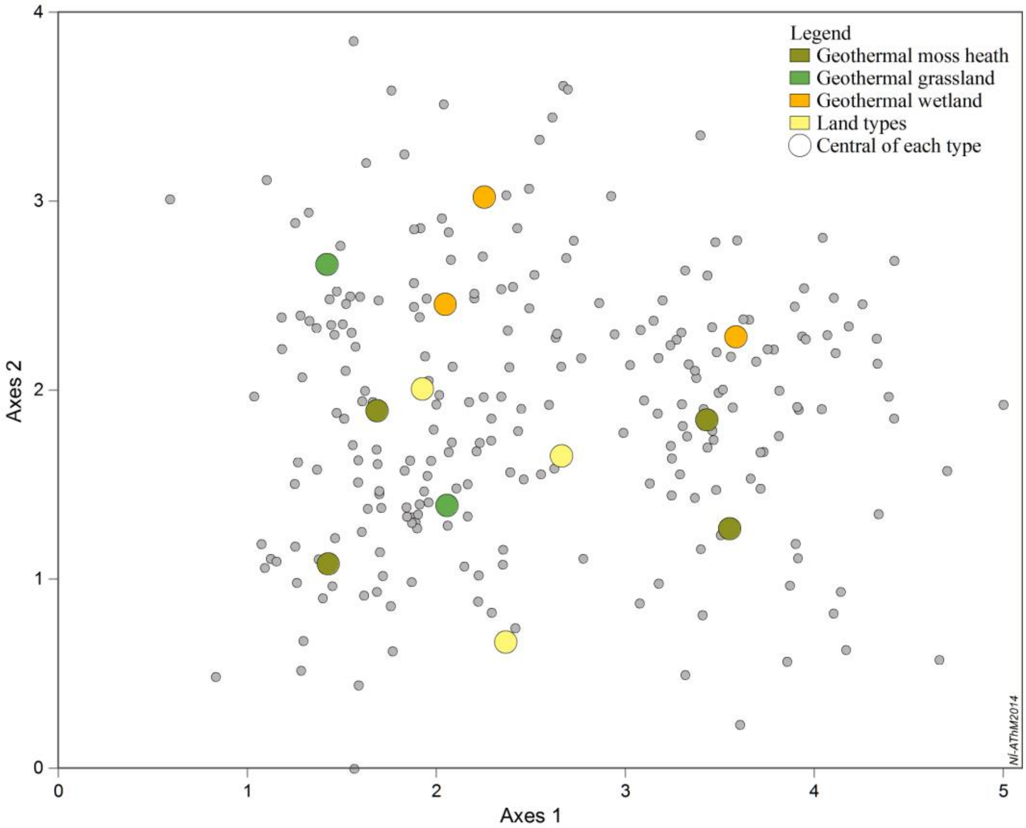


Figure 7. Results of DCA ordination of the three main geothermal vegetation groups and land types. Colored circles indicate the average value for each type, within a group, in relation to the two axes. Data based on polygons where soil temperature was >15°C, studied in 2005-2008.

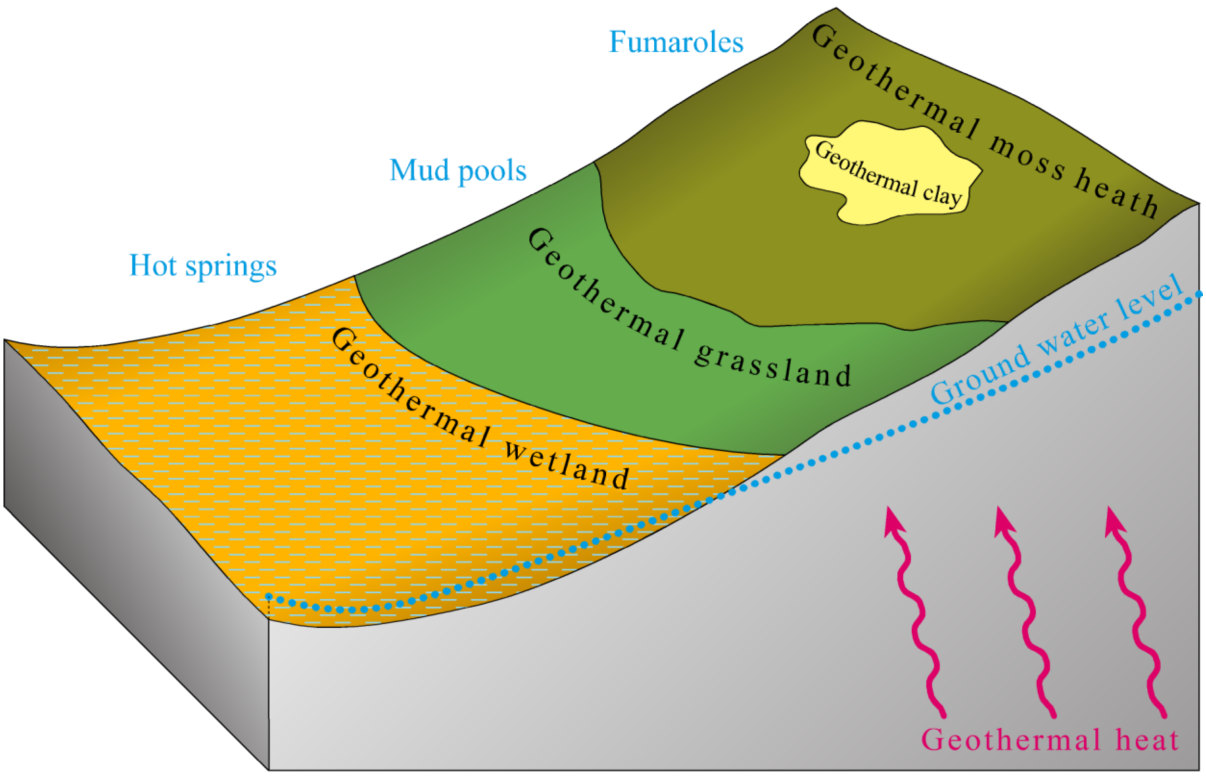
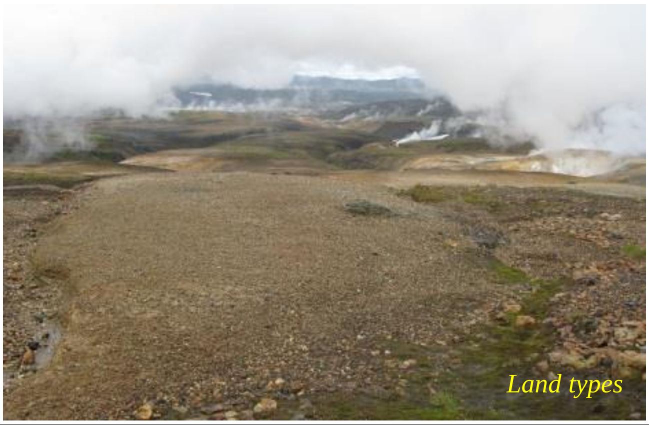


Figure 8. Simplified landscape explanation of geothermal heat, ground water level, geothermal features and distribution of the three main vegetation groups of geothermal areas in Iceland.

Table 3. Description of the three main groups of the vegetation types and the land types.

Main groups	**Vegetation** **Soil** **Geothermal features**
	Mosses dominant with dwarf shrubs, dicots or grasses. Main dominant vascular species are *Festuca vivipara*, *Agrostis stolonifera*, *Thymus praecox*, *Deschampsia alpine* and *Salix herbacea*. Four vegetation types. -------------------- Soil is thin, average soil temperature is 35°C (range 15-98°C). -------------------- Fumaroles and mud pools common.
	Grasses dominant with e.g. dicots and dwarf shrubs. Main dominant vascular species are *Agrostis stolonifera*, *Agrostis capillaris*, *Thymus praecox*, *Argentina anserina* and *Festuca vivipara*. Two vegetation types. -------------------- Soil is rather thick, average soil temperature is 25°C (range 15-52°C). -------------------- Mud pools and hot springs common.
	Mosses, monocots and wetland dicots dominant. Main dominant vascular species are *Epilobium palustre*, *Agrostis stolonifera*, *Carex nigra*, *Juncus articulates* and *Eriophorum angustifolium.* Three vegetation types. -------------------- Soil is water-logged, average soil temperature is 26°C (range 15-49°C). -------------------- Hot springs and creeks are common.
	Limited vegetation cover and few plant species. Main vascular species are *Agrostis stolonifera*, *Festuca rubra*, *Festuca vivipara*, *Plantago maritime* and *Deschampsia alpine*. Three land types. -------------------- Soil is thin and organic material low, average soil temperature is 27°C (range 16-89°C). -------------------- Various geothermal features, e.g. fumaroles, steaming ground and warm streams.

4. DISCUSSION

Relationship between soil and vegetation

Our results show that soil temperature is one of the most important factors determining the composition and structure of vegetation in geothermal fields in Iceland. Thus the total cover and number of plant species decreased gradually as soil temperature increased (Figures 4 and 5). The cover of vascular species dropped below 25% around 50°C soil temperature and the number of species became fewer than ten per 100 m^2. Other researches have similarly shown that vegetation at geothermal sites is closely related to soil temperature in the root zone (Glime and Iwatsuki 1994, Given 1980). Extreme temperature affects metabolic activity in cells and can reduce growth and productivity, for example, although some plant species are adapted to the high temperatures in geothermal areas (Chiarucci et al. 2008, Pavlik and Enberg 2001). Our results are in coherence with others that have shown that both biotic and abiotic conditions are unique within geothermal areas worldwide and affect vegetation structure and composition that can differ greatly from the surrounding areas (Convey et al. 2000, Burns 1997, Halloy 1991). Those studies have shown that geothermal areas are in general characterized by steep gradients in soil temperature and humidity, high acidity and an unusual concentration of minerals and elements.

In contrast to the vascular plants, moss cover and their species number changed considerably less with increased soil temperature (Figures 4 and 5). Other studies have indicated that mosses can survive where soil temperature is high, which can be explained to some extent by the lack of roots and that the soil temperature is lower at the soil surface than at 10 cm depth (Glime and Hong 1997, Given 1980). It can also be assumed that the active parts of mosses are the ends of branches and that the lower part of the moss layer isolates the active parts from most of the heat (Glime and Iwatsuki 1994). This ability of mosses and the fact that vascular species cannot tolerate the heat as well give the mosses an advantage in competition for example space. In our study, lichen species were rarely found where the soil temperature was above 30°C and their cover was negligible. Lichens can, however, grow in a wide range of soil temperatures, but studies have also shown that they rarely grow where the soil temperature and moisture are high (Glime and Hong 1997, Glime and Iwatsuki 1994, Kappen and Smith 1980).

Soil pH influences vegetation both directly and indirectly. Within a majority of our plots, the pH of soil was between pH 5-8 which is common in soils in Iceland and favors nitrogen and phosphorus availability as well as the microbiological activity for nitrogen fixation (Magnússon et al. 2009, Arnalds 2004, Tucker et al. 1987). A soil pH of <2 was found in two cases and in both cases the vegetation cover was extremely low (Figure 3). Under such acid conditions the ability of plants to take up nutrients is limited and toxicity, for example from aluminum, is possible which in turn affects the plants negatively (Delhaize and Ryan 1995). Our results show that soil carbon concentration decreased considerably as soil temperature increased. The soil carbon content was below 1% in all plots with a soil temperature >50°C (Figure 3). This carbon content is similar to poor sandy and gravelly soils in Iceland where vegetation is scattered (Magnússon et al. 2009). The pattern of soil carbon concentration in relation to high soil temperature reflects the reduced cover and number of vascular plant species (Figures 4 and 5).

Vegetation types

The results of both TWINSPAN classification and DCA ordination revealed that the vegetation variation of the seventeen high-temperature areas was strongly related to height above sea level and there was good separation between the two groups analyzed with TWINSPAN classification (Figure 6). The DCA ordination also indicated that different vegetation types were found above 800 m a.s.l. than below and that there were fewer vegetation types at high altitudes (Figure 7). The annual temperature is lower, the growing season is shorter and there is more snow at areas above 800 m a.s.l. and these factors have a strong influence on species distribution and composition. Precipitation is another factor that affects the vegetation variation. On the other hand, soil temperature did not have as strong a relation with the variation in vegetation in study 2. The connection between soil temperature and vegetation was more obvious in study 1, which was only limited to six sites with more uniform environmental conditions and vegetation (Figures 4 and 5).

The term geothermal vegetation indicates vegetation composition or vegetation production that is influenced by elevated soil temperature or other factors related to it (Merret et al. 1999). In this study we have used this definition along with soil temperature measurements to separate geothermal vegetation from other types. The distinction in geothermal vegetation types in our study from non-geothermal vegetation in the surroundings was in most cases clear. However, it was most obvious in the central highlands of Iceland where vegetation cover increased at the geothermal spots compared to the surroundings, which are in most cases sparsely vegetated. The distinction was least in the geothermal grasslands and wetlands in the lowlands but the geothermal moss heath was usually clearly separated from its surroundings.

The study showed that the main geothermal vegetation groups were often aligned in zones within the geothermal areas (Table 3, Figure 8). Adjacent to a geothermal feature where the ground water level is low there is light colored geothermal clay where very few plant species exist. Geothermal moss heath becomes prominent, along with a scattered cover of vascular plants, where the direct influences of the geothermal features diminish. Farther away, geothermal grassland develops where soil moisture increases, and when the ground water level intersects the surface a geothermal wetland appears. All these zones or main groups of vegetation do not necessarily exist all together at one site but indicate the environmental conditions at each site. Similarly, vegetation zones have been described at geothermal areas in other countries (Chiarucci et.al. 2008, Convey and Lewis 2006, Burns 1997).

Flora

The number of plant species recorded within the high-temperature areas varied considerably, related to the size of the areas but also to other factors, such as diverse environmental conditions (Table 2). The geothermal areas were at different heights above sea level and those above 800 m a.s.l. were characterized by unfavorable climate with a short growing season, the precipitation is usually high and the mean temperature low. Red listed or geothermal species were found within all of the high-temperature geothermal areas with two exceptions (Table 2). Two red listed vascular species were found, both classified as VU (vulnerable) (Icelandic Institute of Natural History 2014). *Ophioglossum azoricum* is restricted to thermal soils in Iceland and is rare worldwide (Kristinsson 1986). It was found within most of the areas and its distribution showed no connection with height above sea level or precipitation. The other red listed species, *Veronica anagallis-aquatica*, is also a geothermal species that grows in warm springs and creeks. The vascular species *Gnaphalium uliginosum* is a geothermal species that grows in mossy ground or clay flats but is not a red listed species in Iceland. One of the eight red listed mosses, *Dicranella heteromalla,* is classified as LR (lower risk) and is as well a geothermal species. All of these species grow at small spots within the high-temperature areas and care has to be taken to avoid damaging their habitats. Additionally, the moss species *Campylopus introflexus* was recorded that is one of three plant species in Iceland that have been defined as invasive species (Nobanis 2014). It was probably transmitted to Iceland with tourists after 1970 and is now found at geothermal areas both in the lowlands as well as in the highlands.

CONCLUSIONS

The results of these studies give a good overview of vegetation at high-temperature geothermal areas in Iceland and they will be valuable for monitoring vegetation within these areas in the future. A considerable difference was found between the high-temperature areas that reflects the variation in their size, elevation, soil temperature, ground water level and local precipitation (Table 1). All these factors influence flora and vegetation. The information gathered gives an insight into the ecosystems of the areas and are important and contribute to improved decisions for conservation or utilization of the areas, which are under increased pressure from the tourism and energy sectors. The geothermal features of the high-temperature areas in Iceland are without a doubt also valuable and they have recently been described and classified (Jónasson and Einarsson 2009). Few studies have been initiated on the effects of the geothermal power plants or tourism on geothermal vegetation. A recent study of moss heaths around two geothermal power plants in SW Iceland has shown that damage has occurred in the moss carpets around the plants which is probably due to airborne sulfur vapors and trace elements from the plant (Helgadóttir et al. 2013). Permanent study plots have been delineated to follow these changes further in the coming years. Although not studied, it is also clear that trampling is affecting vegetation at popular tourist areas in Iceland, as has been demonstrated in other countries (e.g. Bruns et al. 2013). The preservation and maintenance of key and diverse geothermal sites in pristine condition is very important and needs to be implemented.

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