# **Effect of geothermal soil warming on needle morphology of *Picea sitchensis* in southwest Iceland**

Paige Guevarra
Bates College
paigeyg@yahoo.com

School for International Training: Iceland and Greenland
Climate Change and the Arctic Spring 2017

Project Advisor: Bjarni D. Sigurdsson
The Agricultural University of Iceland

# Table of Contents

## Abstract

This study aims to evaluate how soil warming will affect needle morphology of Sitka spruce (*Picea sitchensis*) and was conducted at the ForHot research site, a geothermal gradient area in south Iceland that represents realistic conditions of soil warming and acts as a proxy for warmer soil temperatures due to climate change. Specific needle area (SNA), needle density, and curved needle length of the most recent year of growth (2016) were assessed as a representation of growth, soil nutrient availability, and external stressors in three strata of trees grown in soil temperature treatments ~ +0 (control), 1, 3, 5, and 10˚C. Using linear regression and in comparison with soil warming, I only found significant changes in the needle density of the lowest stratum and in curved needle length of the highest stratum, with no significant changes in SNA. Although no overarching conclusions could be drawn, I was able to conclude there was no change in soil nutrient status with warming, the increased soil temperatures aided the growth of needles in the lower canopy even if it was due to the thinning of other trees, and that there is some unknown stressor affecting the trees specifically at the top of the canopy. To gain a better understanding of these results, studies should continue investigating soil warming effects on Sitka spruce needles in high latitudes since Sitka spruce is found throughout the worlds subarctic boreal forests and temperate rainforests, can potentially grow large quickly, and could produce profound effects with warming.

## Introduction

Climate has been changing rapidly worldwide since the industrial revolution, during which human inputs of greenhouse gasses (GHG), especially carbon dioxide ($CO_2$), began to increase dramatically. GHGs have raised atmospheric $CO_2$ concentration from a preindustrial level of 278 ppm to 405 ppm, as of January 2017 (Hartmann et al., 2013; Dlugokencky & Tans, 2017), and are projected to reach 490-1370 ppm by the end of the century (Moss et al., 2010). It is widely accepted in climate science that increases in atmospheric $CO_2$ concentration will also increase the mean temperature globally, with an expected increase in global surface temperature anywhere from 1.4-5.8˚C by 2100 (Cubasch et al., 2013). The way in which climate and weather patterns are changing is regionally specific, which is especially true for the arctic and the latitudes from 60˚N reaching up to the Arctic Circle (66.5˚N). As of 2016, surface air temperatures in the arctic were rising at twice the rate of the global average, and in areas above of 60˚N, a +2˚C temperature anomaly was observed in comparison to a 1981-2001 baseline, which also signifies a total increase of 3.5˚C since the start of the 1900s. (Overland et al., 2016). These temperature increases have important implications for the soil and plant communities in the arctic and subarctic.

The northern region of the world is an important site for carbon storage and deposition as it holds the majority of global soil organic carbon, which makes up two-thirds of all carbon in soils (Batjes, 1996; Gianelle, Oechel, Miglietta, Rodeghiero, & Sottocornola, 2010). This quantity of carbon is stored as a result of slow biological decomposition and nutrient turnover. The lack of nutrients often poses a limitation on decomposition and plant growth in high latitudes. It has been postulated that warmer soil temperatures may change this as decomposition increases with warming soil temperature. This could cause carbon storage abilities of soils in northern latitudes to change from a carbon sink to a carbon source (Schimel et al., 2001). This change is already occurring in subarctic and arctic areas, releasing not only $CO_2$, but other GHGs (methane and nitrous oxide) as well (Voigt et al., 2016). In south Iceland at the ForHot study site, a geothermal study site that represents realistic conditions of soil warming, the rate of decomposition of relatively easily decomposable organic material was significantly increased in the three distinct sites studied: recently warmed forest and grassland, and long-term warmed grassland (Sigurdsson et al., 2016). Increased warming, decomposition, and nutrient turnover is therefore not isolated to any one ecosystem type, and has the potential to affect plants as their roots are nestled into the soil and they are important regulators of carbon release or storage.

Specifically, many experiments have looked at the effect that warming of soils has on forest productivity in high latitudes. In a field study (Jarvis & Linder, 2000) in Flakaliden, Sweden, soil warming over a five-year period increased stem-wood growth in Norway spruce (*Picea abies*) trees by more than 50% relative to the control treatment. In a similar subarctic boreal forest in northern Norway, a six-year study on Norway spruce with artificially warmed soil (5˚C above the control) and increased nitrogen availability, found that warmer soil independently and in combination with increased nitrogen availability increased forest productivity (Strömgren & Linder, 2002). In both of these studies, the higher soil temperature may have increased decomposition that in turn increased nitrogen availability in these generally nitrogen limited environments, which was postulated about the Flakaliden study in Sigurdsson et al. (2016). Another warming experiment conducted at the Flakaliden site found that warming only air did not have this effect. It was thought that there must be other important processes occurring in the soil that were allowing the growth of Norway spruce to be altered (Sigurdsson et al., 2013).

In this study, the effect of various degrees of soil warming on the needle morphology of Sitka spruce were investigated at the ForHot study site, which experiences natural warming of soil from +0-52˚C (ForHot Background, n.d.). One of the three study sites at the ForHot site is a 50-year-old Sitka spruce forest in south Iceland that has been experiencing natural geothermal soil warming for the past eight growing seasons (2008-2016) since a shift of geothermal gradients occurred following an earthquake on May 29, 2008. As mentioned previously in a case study about the study site, Sigurdsson et al. (2016) has suggested that the geothermal gradients allow for realistic conditions of soil warming to have an effect on the terrestrial ecosystems with little interference of other environmental conditions. These potentially interfering environmental conditions could include geothermal water in the root zone or changes in soil pH. It is important to note that soil warming over the three-year period also remained relatively unchanged and still followed seasonal cycles in comparison to the control (+0˚C) plots. With this information, five levels of soil warming (~ +0 - control, 1, 3, 5, and 10˚C) were utilized in relation to Sitka spruce needle health and morphology in three strata and the most recent age class (2016 growing season).

In relation to the larger implications of this study, the relationship between warmer soil temperature with nutrient availability and potential $CO_2$ release from soils are of interest. It is possible that more $CO_2$ would be released from the soil through respiration in decomposition and would be sustained without decline. This is supported in a study that found microbes are able to acclimate as their temperature sensitivity decreases at higher temperatures, meaning that there could possibly be an increase in release of $CO_2$ (Lu et al., 2012). This could potentially be mitigated with an increase in nutrient turnover that stimulates tree growth and deposition of carbon as woody biomass. We must also consider the instance in which soils are too warm that carbon deposition through biomass growth is limited, in which $CO_2$ would still be released through decomposition but less would be stored as biomass.

To a further extreme, we should consider the actual upper limit of rapid change in soil temperature that Sitka spruce can withstand. It was established in Sigurdsson et al. (2016) that all Sitka spruce trees in +20˚C plots died, which may have been a result of soil temperatures warming too rapidly for trees acclimate to if acclimation was possible at all. If this occurred on a global scale throughout subarctic boreal forests and temperate rainforests, a potential decrease in usual $CO_2$ sequestration and an increase in decomposition of deceased trees could raise atmospheric $CO_2$ concentrations. Forest growing seasons (high sequestration) of higher latitudes are responsible for the reduction of atmospheric $CO_2$ in summer and the increase in $CO_2$ during the winter (low sequestration), and therefore could have a large impact with current and impending climate change. However, if an increase in warming does not negatively affect Sitka spruce, the population may be able to migrate north as areas covered in permafrost experience melting and soils are able to support Sitka spruce. This way, some of the effects of warming and increased decomposition may be able to be mitigated better than if all of the stands were deceased. With these potential outcomes in mind, I hypothesize that an increase in warming would promote the health and survival of needles in all strata as a result of an increase in soil nutrient turnover, especially of limiting nutrients.

## Methods

*Site Description*

This study was conducted in south Iceland at the ForHot research site, where a natural geothermal gradient has been utilized in studies for over 50 years. The ForHot site is located on the Reykir campus of the Agricultural University of Iceland near to Hveragerði (64.008˚N, 21.178˚W; 83-168 m a.s.l.) (Fig. 1; Sigurdsson et al., 2016). Soil consists of a silty loam volcanic soil type called Silandic Andosols or Brown Andosols (IUSS Working Group WBR, 2015; Arnalds 2015), and often freezes for a few months during winter but warms up for the growing season that lasts from the end of May to the end of August. The site of focus at the ForHot study site is one that warmed in 2008 and consists of Sitka spruce as the main vascular plant, making up 7% of plant cover in the site. The spruce stand was planted in 1966-1967, has never been thinned, and therefore has higher stand density, basal area, and leaf area index in comparison to managed forests of similar ecosystems (Sigurdsson et al., 2016). In 2013, when isotherms and permanent study sites were established, the stand had a dominant height of 10.3 m, diameter at breast height of 12.6 cm, basal area of 49 $m^2$ $ha^{-1}$, and density of 4.461 trees $ha^{-1}$ (as cited in Sigurdsson et al. 2016).


**Figure 1**. Satellite map of the ForHot Sitka spruce (*Picea sitchensis*) forest study site (red x) on the Reykir campus of the Agricultural University of Iceland (yellow x) in relation to Hveragerði, Iceland (64.008˚N, 21.178˚W) (*Google Earth*).

*Sampling Plan*

In fall 2012 and spring 2013, five ca. 50 m long transects were created perpendicular to, or cutting across, the five soil warming levels of ~ +0 (control), 1, 3, 5, and 10˚C, referred to as treatment A, B, C, D, and E, respectively (Fig. 2) (Sigurdsson et al., 2016). In 2013 five replicate 1 $m^2$ permanent study plots were established in each soil warming level, resulting in a total of 25 plots. A sixth warming level of 20˚C did exist at the site, but was not included in the study since all of the spruce trees in this area died.

A total of 39 trees were included in this study and were selected on the basis of being the closest dominant or codominant tree to one of the 25 previously established 1 $m^2$ plots (Fig. 3).

Sometimes, two or three trees were selected at one plot and their values were averaged so that there were still a total of 25 sampling units, yielding five replicates per temperature treatment.

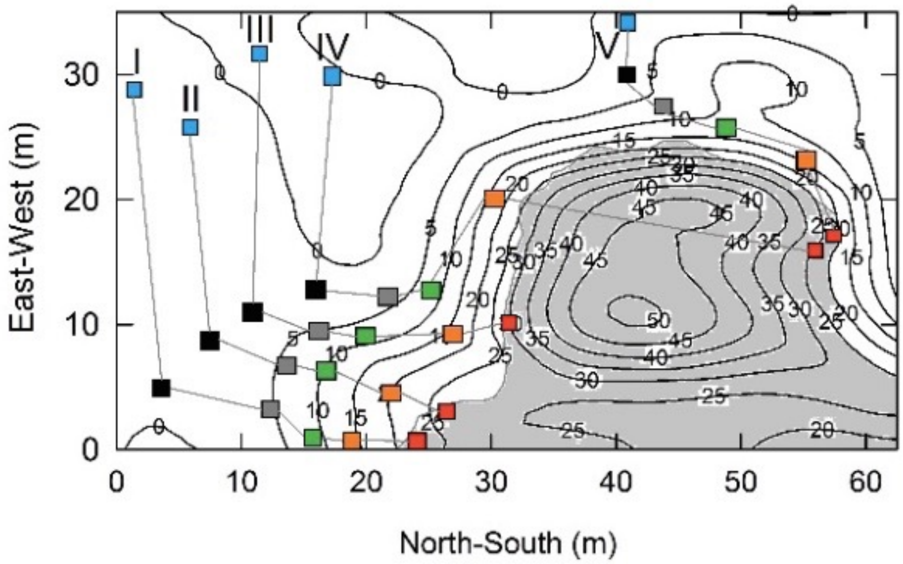


**Figure 2**. Location of soil warming isotherms (˚C) with five 50 m long transects established at the ForHot study site in south Iceland in fall 2012 and spring 2013. The warming levels in this study include A (control, +0 ˚C; blue), B (+1 ˚C; black), C (+3 ˚C; grey), D (+5 ˚C; green), and E (+10 ˚C; orange). Not included in this study is warming level F (+20˚C; red) in which all Sitka spruce (*Picea sitchensis*) died (adopted from Sigurdsson et al., 2016).

**Figure 3.** Example of (A) 1 $m^2$ plot design with sampled trees at the ForHot study site on the Reykir campus of the Agricultural University of Iceland.

On March 6, 2017, the samples from each of the 39 dendrometer trees and 19 additional scaffold tower trees were collected. First, the living crown was divided into three equal strata with stratum one at the top, stratum three at the base, and stratum two in the middle. Three strata were included in this analysis since it has been observed that needle morphology changes most with the changes in strata as opposed to manipulated variables, such as atmospheric temperature or $CO_2$ (Stefansdottir, 2006). Fifteen-meter branch cutters were used to cut branch samples from the south side while following certain specifications in each strata, and then samples were frozen for future laboratory analysis of morphological features on fresh needles. Branches were to be collected with the intention of selecting branch samples from specific orders and specifications in different strata. Stratum one branch samples were to be collected 3-7 whorls from the top with at least the two most recent age classes, or years of growth (C+1 and C+2, C being "current year") and to be first order, meaning the branch first growing from the stem of the tree. Stratum two branch samples were to be collected with at least C+1 and C+2 growth from the second order, or the branches that branch off from the first order. Stratum three branch samples were to be collected from the second order with at least C+1 growth.

*Laboratory Morphological Analysis*

The 39 frozen branch samples were stored at the Keldnaholt campus of the Agricultural University of Iceland until late April and early May 2017 when preparation work for morphological analysis began. Branch samples were first divided into age classes based on the most recent year of growth that often appears as a brighter and lighter orange or brown on the underside of the branch (Fig. 4A and 4B). First, the branch order was determined by looking at the buds. A first order branch generally has a larger bud than second order and has many smaller buds encircling it while a 2$^{nd}$ order branch usually has just two lateral buds in one plane. The stem of a 1$^{st}$ order branch is also much thicker than a 2$^{nd}$ order branch and generally has many shoots branching off arranged in whorls around the shoot, whereas a second order branch generally has shoots branching off in pairs and in one flat plane.

Branch order was determined so the samples collected were definitely from the 2$^{nd}$ order, which previous studies have determined are greater contributors to total needle area than 1$^{st}$ order needles (Stefansdottir, 2006). Third order was not used since there would not be enough third order needles in the first strata to collect samples from. There were a few instances in which no

2nd order shoots were available so that a 3rd order was sampled, or a mixture of 2nd order and 3rd order shoots were sampled. A mixture of 2nd order and 3rd order shoots generally occurred when there were one or two places on the 3rd order shoot that clearly grew and produced needles in 2016 and there were none in the 2nd order. The third order sample would be cut as the most recent year of growth, and the remainder of the age class samples would be cut form the 2nd order. Growth segments were counted from both orders to verify that the years of growth lined up correctly with one extra year of growth (2016) in the third order.

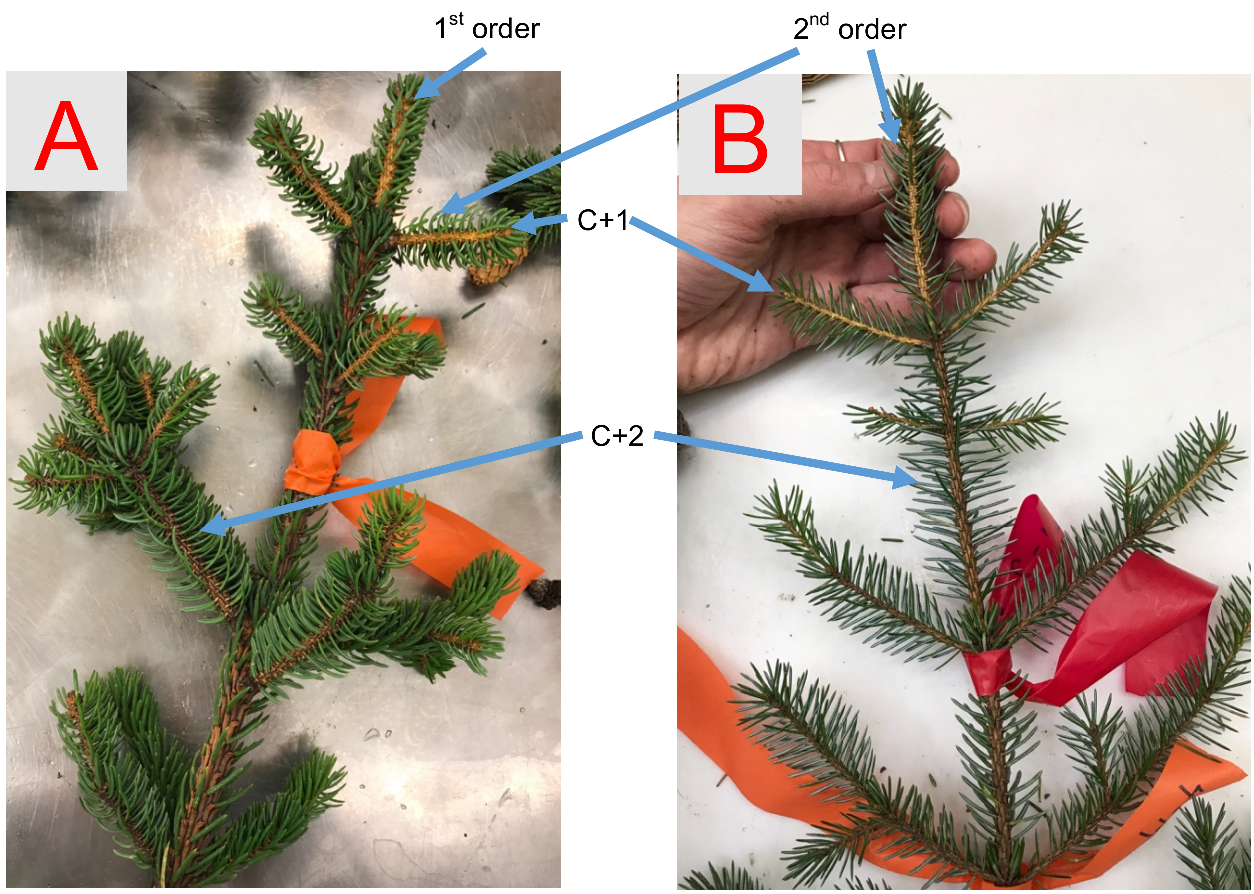


**Figure 4**. Example of a (A) first order stratum one sample and (B) second order stratum two sample from Sitka spruce (Picea sitchensis) in which the most recent growth (C+1) is a bright or light orange or brown and the orders of shoots are identified.

The shoots were divided into four annual age classes with scissors and hand pruners as best as possible: C+1 (2016), C+2 (2015), C+3 (2014), and C+N (any year including or before 2013). Many branch samples did not include growth past C+2, but the goal was to have samples of at least C+1 and C+2 growth. Each sample was cut to have ca. 30 needles on the shoot (usually between 1-4 cm in length) and measured with a digital caliper. In addition, all of the second and third order C+1 samples were also removed from the branch to be used later in chemical analysis. Each sample that was divided into age classes and samples for chemical analysis were stored in stapled, individual paper bags, and returned to the freezer to preserve the living characteristics for image analysis.

An image analysis program, winSEEDLE™ (Version 5.1A, Regent Instruments Inc., Blain, QC, Canada) was used to determine length and width of each needle, as well as the total area of all needles, an important parameter for determining soil nutrient status. Samples were removed from the freezer a few at a time in an attempt to keep samples fresh. One sample at a time, shoots and any loose needles were removed from the bag, needles were removed from the shoot, and any extra part of the shoot connected to the needles was removed with a surgical scalpel. If needles broke, the number of broken needles per sample were noted for later calculations, but were not included in the analysis. Needles were arranged on a scanner such that no needles were touching, and the needles were scanned and analyzed by the winSEEDLE™ program. The needles were then returned to the bag, stapled, and saved for drying and weighing.

Following winSEEDLE™ analysis, needle samples were dried to obtain the dry weight. Samples were all dried at a target of 80˚C for at least 48 hours and then weighed with an accuracy of 0.0001 g. Samples were saved in case they are needed in the future.

*Data Analysis*

Excel was used for data analysis of specific needle area (SNA) and needle density. Using the area output from winSEEDLE™, SNA was calculated with the formula: SNA= A/DM, where A is projected fresh needle area in $cm^2$ and DM is dry mass of needles in g. Needle density was calculated as the number of needles per cm of twig, and was calculated using the formula: (No. extra needles + No. of winSEEDLE™ needles)/length of shoot in cm, where no. of extra needles is the number of needles that have broken in the process of removing needles from the shoot and no. of winSEEDLE™ needles is the number of needles provided in the output of data following analysis with winSEEDLE™.

Excel was used for statistical analysis with a level of significance of 0.05. Only the samples of most recent year of growth (C+1) in each stratum were analyzed for SNA, needle density, and curved needle length, an output from the winSEEDLE™ program. Before any analysis began, the values for the samples that were taken from the same tree were first averaged so that there were a total of 5 sample values for each soil temperature warming level. To see if there were any significant changes with soil warming, linear regressions were performed individually for each variable and stratum (i.e., SNA stratum one, or the "top" of the tree) with the mean annual soil warming at a 10 cm depth. If any data points were missing, the data point was excluded in the linear regression.

### *Ethics*

This is a natural science study and does not involve human or animal participants. Therefore, there were not any ethical challenges or conflicts of interest as only a group of trees in an already naturally warm area were being studied. I tried to avoid biases when collecting, interpreting, and presenting data.

## Results

With increasing soil warming, needle density was significantly greater in the lowest canopy and curved needle length was significantly decreased in the lowest canopy. There was no significant change in specific needle area in any strata with warming. Overall, little of the variability in any of the three variables investigated can be explained by soil warming.

### *Specific Needle Area*

There is no significant change in SNA of needle growth from 2016 in any strata with soil warming, and therefore nothing definitive can be said about the relationship between soil warming and SNA of any strata. In addition, very little of the variability in SNA is explained by soil warming as the $R^2$ values are all less than 0.05.

### *Needle Density*

Needle density of the most recent year of growth (2016; C+1) in all three strata is shown in Figure 5. Through observation, the highest needle density is in the top stratum and the lowest density is in the middle and bottom strata in no particular order since the regression lines overlap. Although these observations can be made looking at the figure, the bottom stratum is the only level that actually exhibits a significant change in needle density with soil warming (Table

1). As soil warmed, needle density in the bottom stratum increased. Nothing definitive can be said about the relationship between soil warming and needle density in the top and middle strata. Again, very little of the variability in needle density is explained by soil warming as the $R^2$ values of the top and middle strata are less than 0.09, but the bottom stratum has a higher $R^2$ value of 0.19 (Table 1).

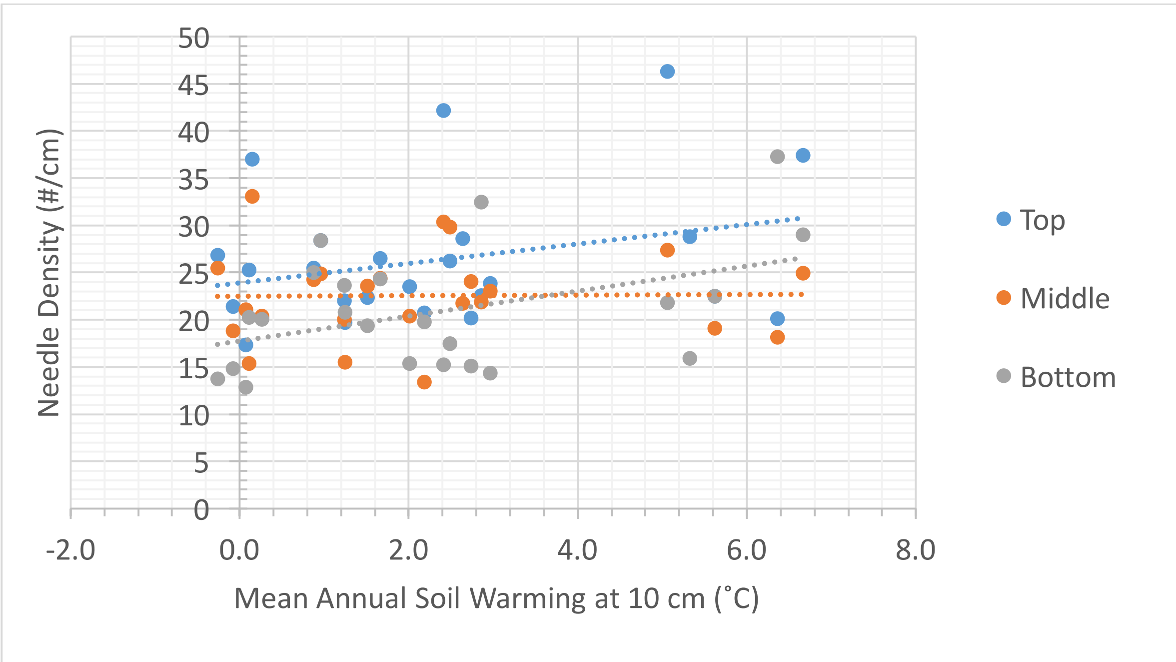


**Figure 5.** Needle density of the most recent year of growth (2016) in three strata of Sitka spruce (*Picea sitchensis*) grown in five soil warming levels at the ForHot study site in south Iceland. Mean annual soil warming is relative to the mean of A plot temperature Top n= 25, middle n= 25, and bottom n= 23.

**Table 1.** Regression analysis of the effect of soil warming on needle density in three strata (canopy levels) of *Picea sitchensis* grown at the ForHot study site in south Iceland. Analysis was made with 2nd order shoots. P<0.05 is a significant effect and is signified with *.

| | Needle Density | | |
|---|---|---|---|
| | Top | Middle | Bottom |
| Regression | 0.16 | 0.45 | 0.037* |
| $R^2$ | 0.086 | 0.025 | 0.19 |
| Slope | 1.035 | 0.408 | 1.32 |
| Intercept | 23.88 | 22.14 | 17.77 |
| N | 25 | 25 | 23 |

*Curved Needle Length*

Curved needle length of the most recent year of growth (2016; C+1) in all three strata is shown in Figure 6. Looking at Figure 6, it is difficult to identify any trends among the strata as the top stratum regression line cuts through the middle and bottom strata, however, it seems possible that the middle stratum overall may have a greater curved needle length than the bottom stratum. Although these are postulations based on the appearance of regression lines in the figure, the top stratum is the only level that actually exhibits a significant change in curved needle length with soil warming (Table 2). As soil warmed, needle density in the top stratum decreased. Nothing definitive can be said about the relationship between soil warming and curved needle length in the middle and bottom strata. Similar to needle density, little of the variability in curved needle length is explained by soil warming in the top and middle strata which have $R^2$ values less than 0.05, but the top stratum has a higher $R^2$ value of 0.17 (Table 2).

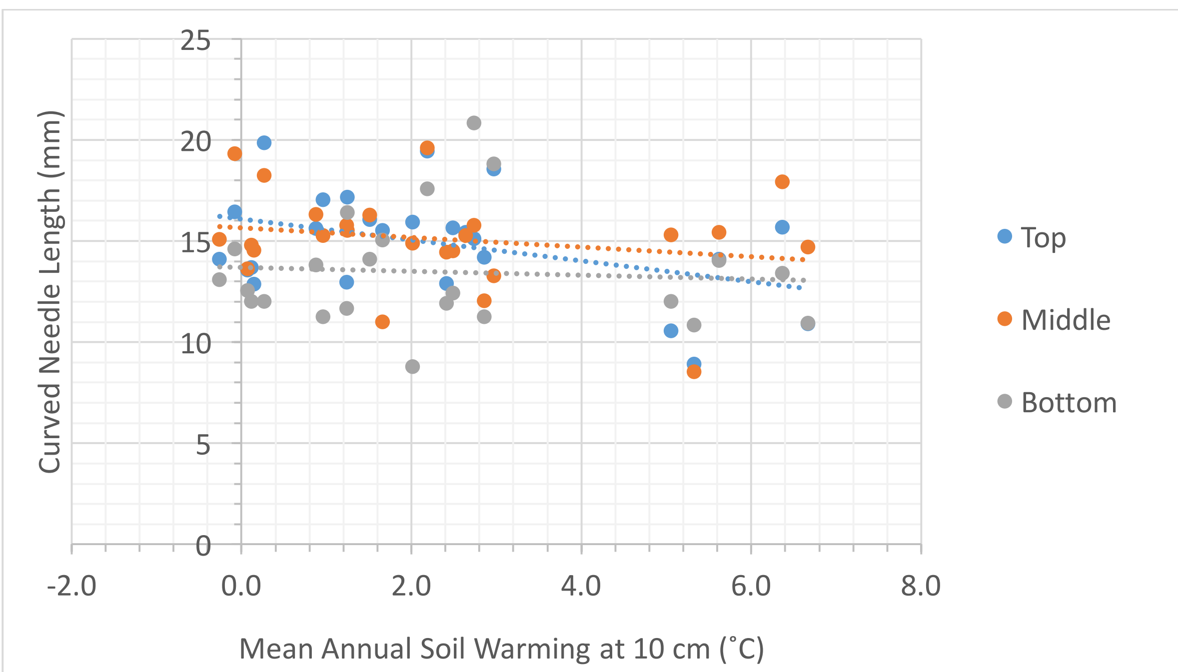


**Figure 6.** Curved needle length of the most recent year of growth (2016) in three strata of Sitka spruce (*Picea sitchensis*) grown in five soil warming levels at the ForHot study in south Iceland. Mean annual soil warming is relative to the mean of A plot temperature. Top n= 25, middle n= 25, and bottom n= 23.

**Table 2**. Regression analysis of the effect of soil warming on curved needle length in three crown levels of *Picea sitchensis* grown at the ForHot study site in south Iceland. Analysis was made with 2nd order shoots. P<0.05 is a significant effect and is signified with *.

| | Curved Needle Length | | |
|---|---|---|---|
| | Top | Middle | Bottom |
| Regression | 0.043* | 0.32 | 0.75 |
| $R^2$ | 0.17 | 0.043 | 0.005 |
| Slope | -0.515 | -0.239 | -0.0942 |
| Intercept | 16.08 | 15.66 | 13.69 |
| N | 25 | 25 | 23 |

## Discussion

The goal of this study was to determine if a relationship existed between soil warming and variables of needle morphology, such as SNA, needle density, and curved needle length, in the most recent year of growth (2016) in Sitka spruce. The only variables in which this relationship existed were needle density in the bottom stratum and curved needle length in the top stratum with no relationships between soil warming and SNA in any strata. Most of these results were surprising to actually see but logical, and only partially support the hypothesis that an increase in warming would promote the health and survival of needles in all strata as a result of an increase in soil nutrient turnover.

No significant changes in SNA of any strata with soil warming was a somewhat unexpected result because SNA is considered to be directly related to soil nutrient status and I had based my hypothesis on an increase in soil nutrient turnover. A lack of significant changes in SNA in any strata with soil warming means that nutrient status had no effect, or must be relatively similar in all warming levels. My hypothesis must be rejected because it was partially based on an increase in nutrient turnover as a product of decomposition as the reason for improved health and survival of needles. It is possible that the microbes responsible for decomposition could have acclimated to the changes in soil temperature, which was suggested in a manipulation based study that also said microbes can become less sensitive to temperature changes as temperatures increase (Lu et al., 2012). Related to acclimation, another study (Melillo et al., 2002) suggested soil warming significantly increased soil respiration only for the first 6 years of a 10-year study. Although this study was conducted in a mid-latitude hardwood forest rather than a high latitude coniferous forest, it appears that similar principles apply across both regions and forest types. This study might not be able to see any changes in the samples currently analyzed if rates of decomposition and nutrient turnover were only increased in the first few years and have since acclimated.

Needle density results were also surprising since the only significant relationship found was that needle density in the bottom stratum actually increased with soil warming, rather than in the upper stratum or in all strata. Needle density relates to resource allocation and the presence of any stressful climate conditions (Salminen & Jalkanen, 2006). Usually in the bottom stratum, needle density is quite low due to the lack of light and availability of nutrients. This is supported by an *in situ* study that investigated the affect of light availability in a few strata and needle morphology of Norway spruce that found needle density often increases with tree height (Niinemets & Kull, 1995). Although our results contradict this, there is a sturdy explanation in the Sitka spruce forest of the ForHot study site post 2008 soil warming, in which all trees in the +20˚C and fewer trees in both the +5˚C and +10˚C soil warming levels died back due to the heat stress. This dieback in the +5˚C and +10˚C soil warming levels opened up the canopy, allowing more light through to the bottom stratum and even the forest floor where small vegetation now grows. Although the soil temperature conditions worsened and resulted in some tree mortality, the increased light at the bottom stratum of the canopy improved the health of the trees remaining. The trees left can now utilize the available light to produce new needles and retain needles for many more years than generally intended. It is possible that both the new and retained needles are contributing more to the overall productivity, and therefore health, of the tree in comparison to trees in dense stands that often receive little light in the bottom stratum and may drop needles after a few years. This increase in needle density with soil warming therefore partially supports my hypothesis that the health of the trees will be improved, however the reason why is different than I had initially thought.

A somewhat surprising result was that of curved needle length, in which only the top stratum had a significant change with soil warming. Curved needle length is essentially the same concept as needle length but better represents the needle length since the needles of Sitka spruce are curved. This parameter is a proxy for the growing conditions and is an indication of general stress experienced by the tree. Since there was a trend of decreased curved needle length with warming in the top stratum, that indicates there is some unknown stressor affecting the growth of these needles, and therefore does not support the hypothesis of increased health and needle survival. It is certain that a lack of soil nutrients is not the cause of stress because the SNA did not change across the soil warming levels, but there is definitely something making the growing conditions worse that unfortunately cannot be explained due to the scope of this study. It is important to note that the shoot and needle structures in conifers are determined based on the growing conditions of the past year. So, any signs of stress acting on the Sitka spruce tree samples from 2016 were actually stressors from 2015.

With the data presented from this study, it is difficult to assess how the Sitka spruce trees are doing in different soil warming levels, especially due to the limitations of control over field experiments and in time constraints. In the field, there is always some uncontrolled variability in the soil temperature, nutrient levels, or introduction of hot groundwater that may have affected the trees in ways that we would not immediately know, even though the site was monitored previously and found to simulate natural warming with little other interfering factors. It is necessary to interpret this data from geothermal gradients with caution since geothermal areas often have very specific volcanic soil types, are only warming the ground and do not take processes aboveground into account, and as mentioned previously, there is potential for responses to be seen in the short term that after a few years may return to the baseline before warming. Even in sampling there were a few discrepancies that sometimes cannot be avoided, such as choosing poor samples that cannot actually be utilized or failing to label samples that were chosen and do not follow the protocol established for choosing samples. These circumstances have limited the number of samples actually able to be used in the experiment, and could have produced slightly different results had they been avoided.

In terms of the data collected, there were no clear patterns established: SNA revealed no difference in soil nutrient status in different temperature warming levels, needle density revealed that an increase warming will decrease stand density but improve the health of remaining trees, and curved needle length reveled that the top of the canopy was experiencing an unknown stress. If I had more time to analyze the age class data (age classes C+1, C+2, C+3, and C+N) with my advisor, more conclusive data likely would have been found. With the data from older age classes, I may have been able to develop a better understanding that dates further back into how warming has been affecting the site. SNA may have revealed that at one point there were differences in soil nutrient status with warming. Needle density of the lowest stratum could have been traced back to see when the increased density began and if it correlated with the timing of thinning due to soil temperature stress. The unknown curved needle length stressor in the top of the canopy could have been investigated further.

## Conclusions

Warming of soils in the boreal forests of the subarctic will definitely have some kind of effect on the growth, health, and morphology of Sitka spruce and its needles, even if the exact effect is not yet known. Looking at just the past year of growth, which reflects the 8th growing season in which the effects of warming would be relevant, there was no change in soil nutrient status with warming, the increased soil temperatures aided the growth of needles in the lower canopy even if it was due to the thinning of other trees, and there is some unknown stressor affecting the trees but acting on curved needle length at the top of the canopy. Knowing that warming of only the soil can produce this wide range of changes in the morphology and health of Sitka spruce needles is valuable in the areas of environmental and climate change research. Many previous studies have looked at warming of just the air around coniferous trees in high latitude boreal forests (Stefansdottir, 2016; Sigurdsson et al., 2013), while fewer have investigated the effects of only warming the soil. Therefore, this study is incredibly important as an early indicator of vague positive and negative changes that Sitka spruce in boreal forests may endure with impending soil warming.

Since there was no change in soil nutrient status with changing temperature, it is difficult to postulate what may be happening in the soil with microbial decomposition, nutrient turnover, and their contributions to climate change as carbon sinks or sources. Unfortunately, no arguments can be made about soil in relation to other forms of carbon deposition, such as storage of carbon as woody biomass. Even guessing how canopy processes, such as gas exchange in photosynthesis or transpiration, may change with soil warming cannot be estimated since soil warming will mostly affect soil and root processes. If any of these variables mentioned can be sorted out in future studies or experiments, a solid argument could be made about the potential of $CO_2$ presence in the atmosphere, its contribution to climate change, and its possibilities of being mitigated by the growth of coniferous trees, such as Sitka spruce. If Sitka spruce were able to withstand soil warming and somewhat mitigate the effects of atmospheric $CO_2$, there could be profound effects worldwide.

*Future Work*

This study aimed to fill a gap that exists in the current knowledge about how the morphology of coniferous trees in this region will be altered as a result of only soil warming, not atmospheric warming. Although this was a good starting place, it will be most important to continue this study as new students will be this summer. The remainder of the data that was not analyzed and the preparation work I began for morphological analysis of the scaffold tower tree samples will both provide a much better understanding of how needle morphology and the general health of Sitka spruce are being affected by soil warming. It is important to continue this study into the future to observe the effects of soil warming over a much longer time period to better assess the effects of long term soil warming on Sitka spruce stands. Similar studies could be set up in other geothermal areas of Iceland where Sitka populations exist to assess if multiple sites produced similar results, which would strengthen the arguments presented in this paper and in other related papers that will be written on this project in the future.

## Acknowledgements

I am grateful to those who initially set up the ForHot study site in 2012 and 2013, the contributors of Sigurdsson et al. (2016) for their assessment of the validity of the ForHot study site to represent realistic soil warming conditions, and to Bjarni D. Sigurdsson and Páll Sigurdsson for collecting all of the samples from the ForHot research site in March 2017. I would also like to thank Bjarni D. Sigurdsson, my advisor, for allowing me to work on this project, guiding me throughout the entire process, and taking the time to make sure I was getting to experience associated field work with other colleagues with similar experience and interest. Thanks is extended to Gunnhildur Eva G. Gunnarsdóttir for helping in lab and with transportation, to Ólafur Eggertsson at the Mógilsá campus of Skógrætin for helping with the winSEEDLE™ program and transportation, and to Jennifer Smith and Daniel Govoni for support throughout the writing process.

## References


Arnalds, O. (2015). The soils of Iceland. Dordrecht, Heidelberg, New York, London: Springer.

Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science, 47*(2), 151-163. doi:10.1111/j.1365-2389.1996.tb01386.x

Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald and J.-G. Winther, 2013: Introduction. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.- K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 119–158, doi:10.1017/CBO9781107415324.007.

Dlugokencky E. & Tans, P. (2017). Globally average marine surface monthly mean data. Retrieved from https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html

ForHot Background. (n.d.). Retrieved from http://landbunadur.rala.is/landbunadur/wgrala.nsf/key2/hhjn8s6hhm.html

Gianelle, D., Oechel, W., Miglietta, F., Rodeghiero, M., & Sottocornola, M. (2010). Cataloguing Soil Carbon Stocks. *Science, 330*(6010), 1476-1476. doi:10.1126/science.330.6010.1476-c

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai, 2013: Observations: atmosphere and surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 159–254, doi:10.1017/CBO9781107415324.008.

IUSS Working Group WRB 2015. World reference base for soil resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. *World Soil Resources Reports* No. 106. FAO, Rome. 192 p.

Jarvis, P., & Linder, S. (2000). Botany: Constraints to growth of boreal forests. *Nature, 405*(6789), 904-905.

Lu M., Zhou, X., Yang Q., Li H., Luo, Y., Fang, C., Chen J, Yang X & Li B. (2012). Responses of ecosystem carbon cycle to experimental warming: A meta- analysis. *Ecology* 94, 726-738. http://dx.doi.org/10.1890/12-0279.1

Melillo, J. M., Steudler, P. A., Aber, J. D., Newkirk, K., Lux, H., Bowles, F. P., . . . Morrisseau, S. (2002). Soil warming and carbon-cycle feedbacks to the climate system. *Science, 298*(5601), 2173-2176. doi:10.1126/science.1074153

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., . . . Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature, 463*(7282), 747-756. doi:http://www.nature.com/nature/journal/v463/n7282/suppinfo/nature08823_S1.html

Niinemets, U., & Kull, O. (1995). Effects of light availability and tree size on the architecture of assimilative surface in the canopy of Picea abies: variation in needle morphology. *Tree Physiol, 15*(5), 307-315.

Overland, J., Hanna, E., Hanssen-Bauer, I., Kim, S.-J., Walsh, J. E., Wang, M., Bhatt, U. S., & Thoman, R. L. (2016). Surface air temperature. In Arctic Report Card 2016. Retrieved from http://www.arctic.noaa.gov/Report-Card

Salminen, H. & Jalkanen, R. 2006. Modelling variation of needle density of Scots pine at high latitudes. Silva Fennica 40(2): 183–194.

Schimel, D. S., House, J. I., Hibbard, K. A., Bousquet, P., Ciais, P., Peylin, P., . . . Wirth, C. (2001). Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. *Nature, 414*(6860), 169-172.

Sigurdsson, B. D., Medhurst, J. L., Wallin, G., Eggertsson, O., & Linder, S. (2013). Growth of mature boreal Norway spruce was not affected by elevated [CO2] and/or air temperature unless nutrient availability was improved. *Tree Physiology, 33*(11), 1192-1205. doi:10.1093/treephys/tpt043

Sigurdsson, B.D., N.I.W. Leblans, S. Dauwe, E. Guðmundsdóttir, P. Gundersen, G.E. Gunnarsdóttir, M. Holmstrup, K. Ilieva-Makulec, T. Kätterer, B. Marteinsdóttir, M. Maljanen, E.S. Oddsdóttir, I. Ostonen, J. Peñuelas, C. Poeplau, A. Richter, P. Sigurðsson, P.M. Van Bodegom, H. Wallander, J. Weedon and I. Janssens (2016). Geothermal ecosystems as natural climate change experiments: the ForHot research site in Iceland as a case study. *Icelandic Agricultural Sciences* 29:53-71. doi: 10.16886/IAS.2016.05

Stefánsdóttir, H. M. (2006). Effects of elevated carbon dioxide concentration and temperature on needle morphology and shoot growth in Norway spruce (Unpublished masters dissertation). University of Iceland, Reykjavik, Iceland. – want to check this with colleagues at the Agricultural University of Iceland

Strömgren, M., & Linder, S. (2002). Effects of nutrition and soil warming on stemwood production in a boreal Norway spruce stand. *Global Change Biology, 8*(12), 1194-1204. doi:10.1046/j.1365-2486.2002.00546.x

Voigt, C., Lamprecht, R. E., Marushchak, M. E., Lind, S. E., Novakovskiy, A., Aurela, M., . . . Biasi, C. (2016). Warming of subarctic tundra increases emissions of all three important greenhouse gases – carbon dioxide, methane, and nitrous oxide. *Global Change Biology*, n/a-n/a. doi:10.1111/gcb.13563