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# Open Field Heated Agriculture for Enhanced Crop Production Using Waste Geothermal Steam, Condensate, and Hot Water to Produce Marketable Crops in Iceland

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*Geothermal waste heat, Heated soil, Heated ground agriculture, Cascade utilization, Enhanced growing season, Open field heated heating*

## ABSTRACT

The authors have been developing and field testing an intensive below grade outdoor shallow soil warming system using steam, condensate, municipal hot water, and waste effluent in cascade utilizations from geothermal bore holes. This system can also be referred to as bottom heat or open field heating. Test beds were constructed and studied at the Agricultural University of Iceland, Keilir Institute of Technology (KIT) and Náttúrulækningafélag Íslands (NLFI Spa and Medical Clinic). This technology has also been field tested in New York City using heated green roofs. The experimental gardens in Iceland are approximately 5 by 10 square meters with 5 by 5 control gardens. The soil depths are between 10 and 20 centimeters (cm) over a plastic piping system that is analogous to a heated sidewalk. Throughout the year water is circulated at a temperature between 45 and 65°C. At 10 cm depth the soil is maintained with a temperature gradient between 20 to 35°C. The growing seasons are extended by more than four weeks, with an average seasonal growth increase of 20%, and harvestable out of range cultivars that normally grow in warmer climates. The gardens in Iceland have produced small marketable harvests of oregano, turnips, zucchinis and celery. The initial small scale test marketing in 2018 was successful. The commercial viabilities of this technology should be investigated.

## 1. Introduction

Open field heated agriculture systems for geothermal settings in Iceland have been investigated.

Industrial trends in geothermal energy are to extract 160-350˚C steam from high temperature area bore holes and generate electricity. Afterwards the waste heat can have a temperature of up to 130-160˚C. In Iceland most of this waste heat can be applied toward cascaded utilization in district heating as well as the heating of greenhouses, swimming pools and spas. Heated streets and sidewalks are other common cascade utilizations of geothermal energy in Iceland. The American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) specifications for heated sidewalks are typically the engineering reference for these heated sidewalks.

In Iceland there have been agricultural trials with the outdoor heating of soil (bottom heat). The existing approaches create minimal soil heating in the range of 6-12˚C at a depth of 10-15 centimeters; these outdoor heated ground agricultural systems have pipes that are about 40-80 centimeters below the surface and up to a meter apart and were only heated a few months in the spring (Gunnlaugsson et al. 2013).

Since 2007, the authors developed and have been testing in Iceland year-round shallow systems of outdoor heated ground agriculture. Three gardens were each constructed similarly to heated sidewalks with a total of four different hot water sources being utilized. The first test garden was installed in 2007 at Agricultural University of Iceland near Hveragerdi and is heated using waste geothermal steam condensate through a traditional heat exchanger. The second test bed was installed in 2010 at the Keilir Institute of Technology (KIT) at Asbru in Reykjanesbaer and uses district heating hot water. The third test bed was installed in 2011 at Náttúrulækningafélag Íslands (NLFI Spa and Medical Clinic) in Hveragerdi. It utilizes two sources: a gravity feed to recover the waste hot water from the clinic’s heated pool and the waste hot water from a contiguous geothermal greenhouse.

Since 2006, The Center for Innovation and Applied Technology at The Cooper Union (formerly the Laboratory for Energy Reclamation and Innovation) has been developing systems to utilize waste to increase agricultural production.

The results from Iceland show that plant growth increases 20% and the growing season is prolonged when a temperature of 25º-30º C is maintained year round at a depth of 8 cm. The overall effect on plants is similar to what would be expected in an unheated greenhouse (Dell et al. 2011, 2013a, 2013b). Research at the Harvard Forest on soil warming confirm the benefits of heated ground agriculture (bottom heat) on plant growth (Lux et al. 1991, Farnsworth et al 1992).

## 2. Test Beds

The test beds have an experimental garden and a control garden that are contiguous and receive the same amount of sunlight and precipitation. They are also identical in construction, and maintenance. The control beds do not have any working fluid in the plastic pipes.

Set ehf. in Selfoss, Iceland manufactured the 2.5-cm diameter polypropylene plastic pipes. They were selected because they could survive several freeze-thaw cycles. In the 5 by 10 m (50 $m^2$) Agricultural University of Iceland in Hveragerdi 260 meters of pipe was placed in a spiral pattern with about 5m of pipe per square meter to ensure even heating. As shown in figure 1, the pipes were kept a constant 25-cm apart using the heated sidewalk polypropylene spacer clips that are manufactured by Bergplast ehf. in Hafnarfjörður.

**Figure 1: Garden construction process showing the plastic pipe configuration and the over layers**

After initial field clearing, the beds were placed on a pre-existing 20-30 cm bed of compacted sand that reduces frost heaves, provides positive drainage. The pipes were covered with an additional 4-5cm of compacted sand. Peat soil, peat and sand mix soil and garden soil, covered this substrate with depths of 10 and 20 cm to create six smaller test sub beds in each garden (Dell et al. 2014).

The first test bed was developed in 2007 at Agricultural University of Iceland in at Reykir, Ölfusi near Hveragerdi. Steam and steam condensate at temperatures from 100 to 125°C is supplied from a nearby geothermal bore hole. It its then piped to a traditional shell and tube heat exchanger that was manufactured in Iceland. A pump then circulates water, or a mixture of water and automotive anti-freeze in a closed loop throughout the year. The adjustable temperatures of the working fluid are set between 45˚C in the summer and 65˚C in the winter. Gate valves and a self-acting temperature controller control the flow of the steam and steam condensate that reheats the working fluid. The heat exchanger is 1.5 m higher than the test beds.

A Danfoss AVTB T self-acting temperature controller regulates the working fluid temperature by the steam flow rate. Grundfos UPS 25-60 180 hot water circulator pump controls the working fluid flow rate of 10 liters per minute as calibrated by a Blue-White F-410N 1-inch NPT float flow meter.

Rexotherm KL 2.0 dial thermometers with a temperature range of 0-120°C are connected to the outflow pipe to the garden and the retour line. The temperature difference averages about 10°C.

At a depth of 8 cm, the temperature of the unheated soil is about 10°C during the growing season. The heated gardens average between 20-35°C at the same soil depth, dependent upon the closeness to the pipes and the weather conditions. The thermal cross section shown in Figure 2 below shows typical temperature peaks over the pipes at 25 cm intervals.

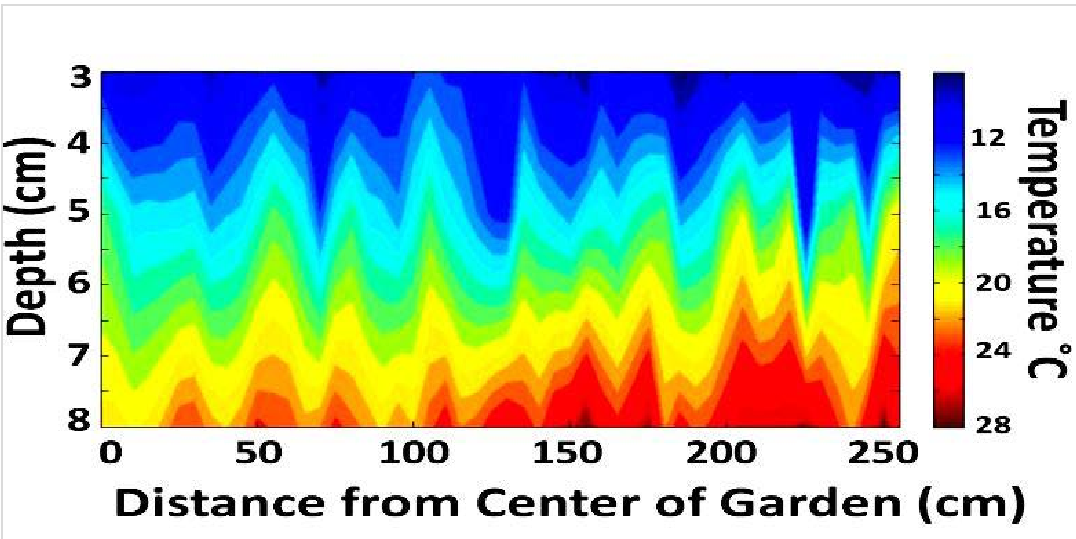


**Figure 2: show the soil temperature from the Hveragerdi experiment.**

The flow rate of the working fluid is a constant 10 liters per minute. The mass of the 80% water / 20% methanol mixture per cubic meter was estimated to be 957 kg/m3 (80% 1000 kg/m3 & 20% 787 kg/m3) and the mass flow rate 0.1595 kg/s. The temperature of the mixture leaving the garden varied between 45°C and 50°C, hence the temperature drop was between 10 and 15 degrees. The average of 12.5 degrees was used for the estimation of the gardens energy consumption. By using an average temperature of 55°C the specific heat of the fluid mixture, Cp, was calculated to be 3.895 kJ/kg.K (80% 4.183 kJ/kg.K & 20% 2.745 kJ/kg.K).

The energy consumption of the garden at the Agricultural University at the end of March, 2014 is calculated using the same procedure as described above. The ambient temperature was 5.6°C, cloudy there was no discernable wind. The temperature of the water sent to the garden was 55°C and the return temperature was 44°C. The value of the flow rate and Cp are 0.1595 kg/s and 3.895 kJ/kgK, The heat transfer calculations are detailed below:

$$\dot{q} = \dot{m}C_p(T_h - T_c)$$

$$\dot{q} = 0.1595\frac{kg}{s} * 3.895\frac{kJ}{kg \cdot K} * (55°C - 41°C)$$

$$\dot{q} = 8.697\ kW$$

$$\dot{q} = 8.697\ kW * \frac{hr}{50\ m^2}$$

$$\dot{q} = 0.174\ \frac{kWh}{m^2}$$

The heat transferred to the garden is thus 0.174 kWh/m$^2$. Note in the calculation above, the heat capacity is a conservative estimate, using a 25% methanol water mix.

The second garden was made in 2010 at the Keilir Institute of Technology (KIT) in Reykjanesbaer. It uses the same municipal geothermal hot water that heats the local Icelandic houses. It has three systems; two have hot water circulation systems that heat the garden, at 40°C and 60°C. Each system has a separate manual temperature controller valve, which controls the temperature and flow of water. The third system has no water and serves as the control garden. Like the geothermal heated houses, the waste water is then piped to the sewers.

As shown in Figure 3, the beds measure 16 by 6 m (96 m$^2$) with 36 separate beds There are six beds at each of three soil depths (10, 20, and 30 cm). These beds are further subdivided into three temperature zones as described above. The beds are divided by preserved wooden panels. The Keilir heated garden has an area of 75 m$^2$. Counting all labor, piping, the control system, and the soil, the garden cost approximately 90 €/m$^2$ to construct.

**Figure 3: Keilir control system and the gardens**

The third garden was installed in 2011 at Náttúrulækningafélag Íslands (NLFI Spa and Medical Clinic) in Hveragerdi. There is a geothermal bore hole that heats the buildings, a swimming pool, and a greenhouse. The open field heated garden was first constructed using the waste hot water from the pool and then the heated greenhouse was added in a second cascade utilization.

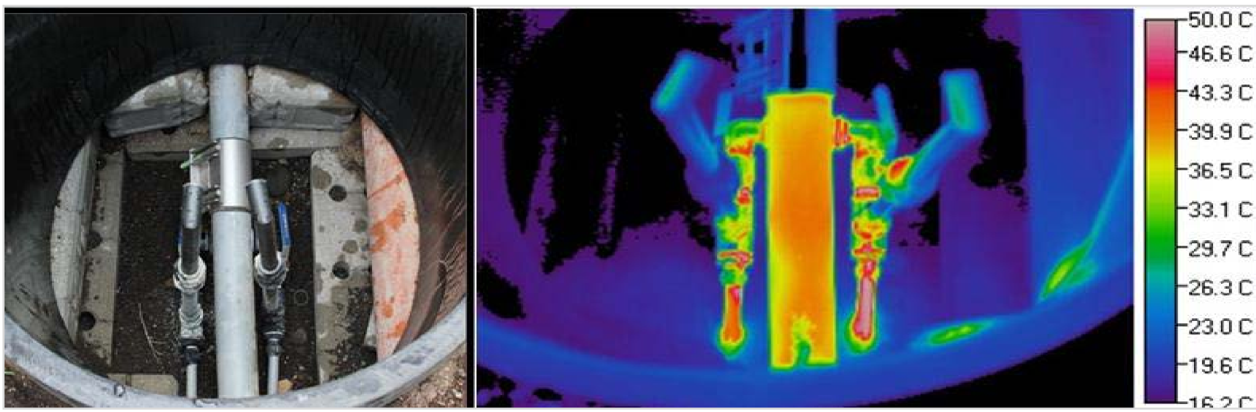


**Figure 4: Pipe tapping connection (left), and infrared image (right)**

The heat exchanger at the swimming pool discharges 55-80°C waste hot water into a 10 cm diameter polybutylene pipe. It runs 80 m via a gravity feed to a cooling pit 7 m. lower in elevation. This gravity feed contrasts to the pump at Agricultural University of Iceland and the system water pressure at Keilir Institute of Technology. The hot effluent from the pool is eventually mixed with cold potable water in the cooling pit, the mixture drains into the nearby Varmá River. This was the first working fluid for the garden. As shown in figure 4, it is tapped from the underside of the discharge pipe with a stainless steel tee repair clamp approximately about 10 m before the cooling pit. Two separate lines run from it to the garden, both lines have separate air venting and flow control valves. *Different t*emperature zones were created by restricting the hot water flow in either of the lines and by controlling the overlaying soil depth. There is again a control section of the garden that has no fluid flow. Both garden pipes discharged into the Varmá River.

A heated greenhouse directly discharges approximately 10 m from the Varma River. A feed from the greenhouse waste hot water discharge was connected to the system in the second cascade utilization for the test bed. This plastic pipe was also tapped using a tee connection that allows the fluid to exit at the bottom of the bottom with a simple a ball valve for flow adjustment. There is approximately 2 m of head from the greenhouse to the garden pipes. This 3 cm diameter tap runs almost 40 m to the heated garden.

All test beds experienced unexpected water shutdowns and temperature inconsistencies due to steam bore hole's temperature response to earthquake activity, and also various equipment failures. The gardens also suffered from periodic wind and vermin damage.

Despite these problems and the basic simplicity of the temperature control systems, there were dramatic consistent increases in overall crop yields and growth that mirrored the Harvard Forest soil heating studies (Lux et al. 1991, Farnsworth et al. 1992).

Different plant types were tested in the heated gardens including indigenous plants and cultivars that normally thrive in a climate that is at least one United States Department of Agriculture (USDA) hardiness zone warmer. The seeds were first germinated in early June in a greenhouse at the Agricultural University of Iceland for a few weeks until each plant was about 15 cm tall. Seedlings were typically transplanted in 10 cm plastic pots.

The metrics for plant growth were plant height, stem spread and stem diameters. As a measurement base for the height measurements as well as a level surface for the plant stem diameter measurements, a 4 cm by 4 cm by 3 mm thick plastic square was placed on the soil near the plant stem. Plant height was measured from the plastic square to the highest point of the plant using a standard folding meterstick. Plant stem diameters were measured at 2 cm from the plastic square using a Mitutoyo digital caliper. The spread was measured with the meterstick in two perpendicular directions, one of them being the maximum spread. The maximum spread was measured between the tips of the leaves in the two longest distance across the plant. The data was typically collected between June and September. The measurements of all tomato plants in each bed were averaged every week.

Tomatoes (*Lycopersicon esculentum Mill*. cv. Butcher Boy, $4^{th}$ of July, and Steak Sandwich) and zucchini (*Cucubuta pepo L.* cv. Sure Thing) were the main cultivars initially chosen for the garden because they are usually easy to grow and maintain. Later research indicated that oregano, turnips, and celery were also excellent candidates.

No special watering frequencies or amounts were instituted for the heated or control (unheated) gardens. No fertilizers or artificial lighting were used in any of the gardens. In both the heated and control (unheated) gardens, all plant selections and plant locations were determined by using assigned numbers drawn from a hat in a double-blind process.

## 3. Results and Discussion

In the 2008 harvest, the heated tomato plants produced 176% more tomatoes and 63% more fresh weight than the control tomato plants. At the start of the 2009 experiments, the average height of both heated and control tomatoes in 10 cm and 20 cm soil were approximately 26 cm. By the seventh week, the height of the heated tomatoes in both soil depths were approximately 50 cm. In contrast, the height of the control tomatoes was 36 cm in the 10 cm soil and 31 cm in the 20 cm soil. The average heated tomato height in the 10 cm and 20 cm soils was between 1.4 and 1.6 times greater than the control garden. Over the seven weeks of data collection both the 10 and the 20 cm soil depths had average stem diameters for the heated tomatoes than the control tomatoes. The average stem diameters for the heated tomatoes in the 10 and 20 cm beds were 1.5 and 1.9 times greater than the control garden diameters. The results for 2009 are summarized in Table 1.

**Table 1: Heated vs. Unheated Tomato Plant Growth in 2009**

| | Growth Factor |
|---|---|
| Average height in 10 cm soil | 1.4 |
| Average height in 20 cm soil | 1.6 |
| Average stem diameter in 10 cm soil | 1.5 |
| Average stem diameter in 20 cm soil | 1.9 |

In 2012, growth data for the tomatoes and zucchinis was collected between June and September. The spread of tomato plants in the heated beds increased by 87 and compared to only 17%, in the unheated control beds. The stem diameter of the tomato plants in the heated and control beds increased by 103 and 43%, respectively. The mass of the ripe zucchini fruits from the heated beds ranged from 293 to 950 g. The mean and median weights were 563 and 506 g. All zucchini plants in the unheated beds died before producing fruit. The stem diameters in the increased by over 83% in the heated beds and understandably less than 2% in the unheated beds. The stem diameter of the zucchini plants in the heated and unheated beds increased by 83% and 2%, respectively. Table 2 presents the results from 2012. Figure 5 shows the heated and control (unheated) gardens for on September 17, 2012.

**Table 2: Heated vs. Unheated Plant Growth in 2012**

| | Growth Factor |
|---|---|
| Average spread of Tomato Plants | 5.1 |
| Average stem diameter of Tomato Plants | 2.4 |
| Average weight of Zucchini Fruit | ∞ |
| Average stem diameter of Zucchini Plants | 41.5 |

**Figure 5: The heated (left) and the unheated (right) 20 cm peat and sand beds Agricultural University of Iceland gardens on Sept. 17, 2012.**

Similar results were observed, particular in the 10 cm garden soil beds as shown in Figure 6 from October, 2015. The difference in growth and maturity was consistent. The heated gardens were productive while most of the unheated gardens had dead plants and those that survived exhibited stunted growth.

**Figure 5: The unheated (right) and heated (left) 10 cm garden soil at the Agricultural University of Iceland gardens on October 1, 2015**

The overall results are re dramatically demonstrated in Figure 6 below, also from 2015, when the turnips reached maturity, again the 10cm garden soil heated beds. The heated turnips from this sample had a mass of 800 to 1,050 grams, while the few unheated turnips produced were between 55 to 25 grams.

**Figure 5: The largest specimens from both beds: that unheated turnip - 55 grams (left) and heated turnip - 1050 grams (right)**

Several years, including 2017, did not have documented harvests due to logistical and financial constraints.

The harvest in 2018 produced marketable crops of turnips and oregano. Figure 6 shows the data throughout the growing season for the 20 cm depth soil. At the end of the season the heated garden crops again showed significant growth improvements. The average height and width of the oregano were from 87 and 105% greater in the heated garden than in the control (unheated) garden, respectively. The average height and width of the turnips were between 157 and 130% greater in the heated garden than in the control garden.

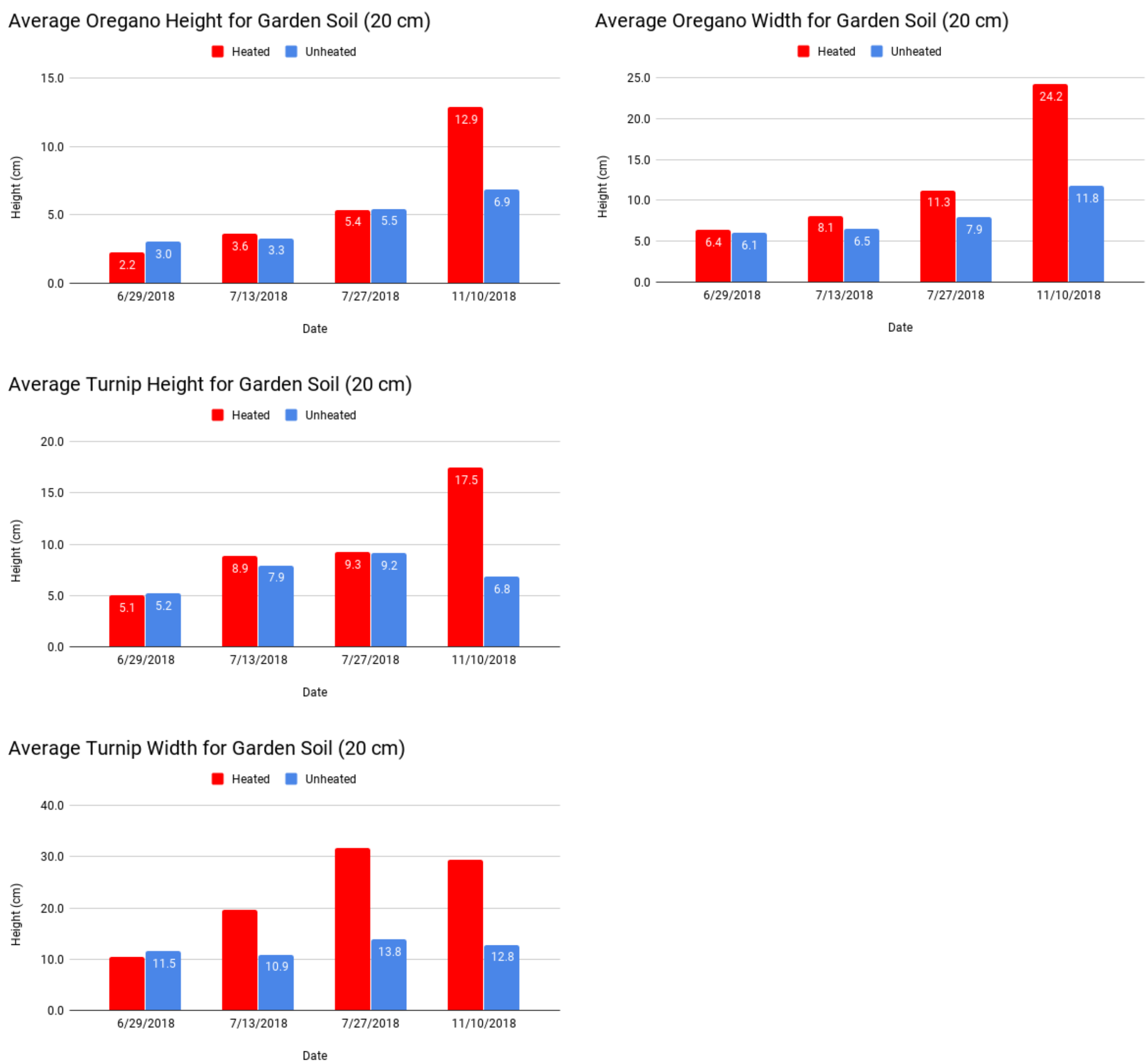


**Figure 6: Growth data for the 2018 growing season in Iceland for oregano height (top left) and width (top right) and turnips height (bottom left) and width (bottom right).**

**Figure 7: (left) October, 2019 one bed of oregano pre- harvest; note shoe in bottom for scale, (right) turnips from harvest in test market setting**

Figure 7 shows one of the heated oregano beds before the harvest and the turnips as displayed at Frú Lauga, an organic food store in Reykjavik. All proceeds were donated to charity in this first attempt at commercialization.

Two non-indigenous 15 cm high oak trees were planted in 2014 in the 20 cm heated and unheated garden soil plots. The unheated oak tree withered and died as expected within one year. The heated oak continues to grow. Oak trees are a rare species in Iceland, which is in general considered too cold for them to survive. As demonstrated in Figure 8 that shows the heated oak tree, grew in to 71.5 cm in height and 88 cm in width by 2018.

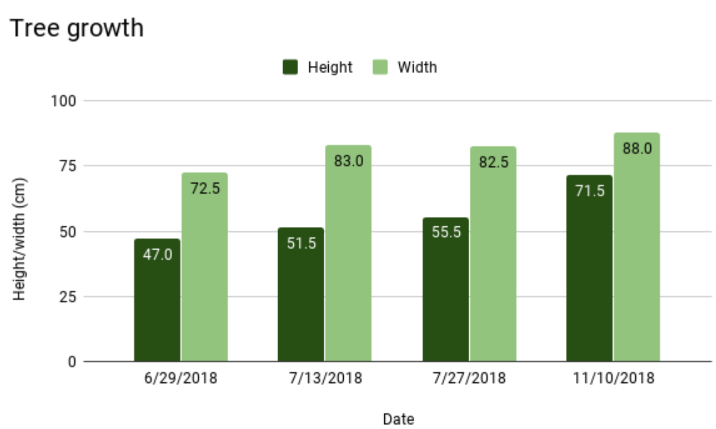


**Figure 8: Oak tree growth data for the 2018 growing season in Iceland.**

Several similar test beds were also studied in raised green roof beds in New York City using waste from a Combined Heat and Power (CHP) system. As can be seen in Figure 8, Cotton, which typically is only harvestable in the southern parts of the country, was grown outdoors to harvestable bolls (Dell et al 2016).

**Figure 9: Cotton plants grown in New York City in unheated (left) and heated (center) gardens. The plants in the heated gardens produced harvestable bolls in October of 2014 (right).**

## 5. Conclusions

The survival and ripening of out of region cultivars, such as tomatoes, zucchinis and other cultivars grown outside during the growing season in Iceland and New York City has been demonstrated. Cultivars that were previously only grown in greenhouses in Iceland can now be grown outdoors. Average plant growth increases more than 20% above the control gardens were also noted. An initial small commercialization attempt was successful justifying the current larger scale efforts. Disposing waste heat in a cascade utilization was successful and further research should clarify the economic viability of large scale commercial operations.

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