Impact of Low-Grade Heat and Insulation on Plant Growth

Undergraduate project supported by the Student Innovation Fund

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Abstract

Large quantities of low-grade hot water are abundant in numerous locations, particularly as a byproduct of power generation. Disposal of such water is generally harmful to the environment (thermal pollution), and allowable discharge rates can become limited during periods of low river flow. Low-grade warm water is particularly abundant per-capita in Iceland, where geothermal wells and power plant outflows are used for a municipal heating system, being discharged at around 30°C. At the same time, while all temperate regions suffer from reduced cultivation potential in cold weather, high-latitude locations such as Iceland experience cool or cold weather during the entire year, significantly reducing cultivation options. Lower-grade heat, however, has reduced potential for maintaining soil temperature relative to higher-grade heat. Consequently, we established a programme to investigate the impacts of (and optimal configurations for) use of thermal wastewater in cultivation with insulated beds. Despite a late start and limited cultivation time, we showed a significant impact of low-grade heating on growth rates.

Keywords: geothermal, thermal pollution, wastewater, heat, soil heat, root stimulation, growing season, cold-climate agriculture, Iceland

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Introduction

Why This Research?

A diverse diet with an increased emphasis on consumption of vegetables is an important part of a healthy lifestyle. Today there is an increased demand for plant-based diets, but Icelanders rely on imported vegetables and fruits to a great degree; indeed, 50% of the Icelandic diet is made of imported calories, including half of all vegetables, sugars, and oils and nearly all fruit, cereals, and beans (Halldórsdóttir & Nicholas, 2016). Today, especially in the wake of the COVID-19 pandemic, there have been increasing calls for a greater degree of self-sufficiency, both in Iceland (Ólafsdóttir 2020; Samband Íslenskra Sveitarfélaga 2020) and in Europe in general (Bruyninckx 2020).

Geothermal heat has long been used for cultivation in Iceland, but only to a limited degree outdoors. Outdoor cultivation in the country is limited by the long winter, and severe winter weather has significant impact on the health of fruit trees and other perennials, which require shelter, sun, and good soil (Guðmundsdóttir 2013). It has been shown that soil temperature is more important than air temperature for some species of importance (Hurd & Graves 1985). Experiments in Iceland with outdoor soil heating have led to greater harvests (Dell et al. 2013), but these experiments have used higher-temperature water, which is in greater demand, rather than wastewater.

In populated areas there exists additional potential for cultivation where conditions are better, with respect to shelter and temperature.

Langagróf, south of Elliðaárdalur, is the planned site for ALDIN Biodome, whose primary activities involve the integration of daily life with plant cultivation. The site is sheltered and sunny. Large quantities of geothermal wastewater (on average 75 litres per second) arrives from nearby neighborhods at approximately 30°C, where it enters the stormwater system and is discharged into the ocean. Utilizing this wastewater would allow for better use of the resource and be beneficial to the environment.

The Research Problem and Objective

Despite the increased demand for plant-based diets, due to weather and conditions is not realistic to cultivate vegetables outside except for limited periods of time. A great quantity of geothermal wastewater at ~30° is discharged and usage of it would be environmentally beneficial.

The goal is to explore whether it's possible to utilize the wastewater at Langagróf to heat the soil and extend the outdoor cultivation period.

Research Questions

1. Is it possible to extend the outdoor cultivation period and have an impact on the size of the harvest and the diversity of species which can be cultivated by means of heating the soil with geothermal wastewater? If so, how much, and how impactful can it be?
2. What cultivation plan is optimal in terms of selected crop varieties and fruit trees?
    a) Soil and insulation
    b) Plumbing depth and flow patterns
    c) Growth progress and cultivation timeperiods

d) Types of plants which can be cultivated (potentially including those not typically suitable to outdoor environments in Iceland)

3. What is the expected cost with setting up such a system, and over what timeperiod can it be repaid?

4. What are the potential benefits for farmers and gardeners in Iceland to implement such a system? *What unexpected environmental impacts might there be from such a system?*

Theoretical Framework

Icelandic Horticultural Tradition and Consumption

Horticulture has existed in Iceland since ithe early settlement period. Landnámabók describes the events leading up to the death of Hjörleifur, brother of Ingólfur Arnarson, as being due to the resentment of his slaves at being forced to drag an ard for planting (Landnámabók). The remains of a 9th-century ard were discovered during an excavation at 3-5 Suðurgata in Reykjavík, confirming that early settlers brought with them the agricultural traditions of the mainland. Over time, however, the increasingly hostile conditions in Iceland during the Little Ice Age led to the abandonment of most horticulture, and between 1400 and 1650 there is little evidence of cultivation outside of the medical gardens of monastaries (Guðnason 2020).

While a number of individuals (such as “Vísi” Gísli Magnússon) helped to try to resurrect gardening in Iceland in the 17th and early 18th century, they faced resistance from a public which found it futile and had grown used to a diet of primarily animal products and imported grain. Serious domestic cultivation efforts did not begin until the “Innrétting” policy of the Danish crown in the mid 18th-century, which mandated vegetable gardens at all large estates. Over time, cultivation of herbs, rhubarb, brassicas, potatoes and other root vegetables became Icelandic staples, but domestic grain production saw mixed results, and most attempts at fruit cultivation were failures (Guðnason 2020). In the early 20th century, geothermal-heated greenhouses began to see significant adoption, a trend furthered by the arrival of fluorescent and then HPS artificial lighting in the latter half of the century. Today, there exists a sizeable greenhouse industry for domestic production of tomatoes cucumbers, lettuce, herbs, cut flowers, and garden / forestry plants; of particular note, locally-grown tomatoes make up 2/3rds of domestic consumption, and cucumbers, 99% (Butrco & Kaplan 2019). However, the high cost of greenhouse cultivation limits production to only high-value products.

Iceland’s domestic food market is unusually vulnerable to disruption among developed nations. The 2008 financial crisis led to a rush on stores as a result of food exporters hesitating to do business with Iceland out of financial concerns, nearly exhausting warehouse supplies of some foodstuffs. A subsequent risk assessment report found that a protracted cessation of imports would lead to Iceland being unable to feed its population; despite recommending specific actions to increase food security, little action was taken. Two years later, the Eyjafjallajökull eruption simultaneously damaged domestic yields and interrupted imports; several minor food shortages occurred as a result. (Butrco & Kaplan 2019).

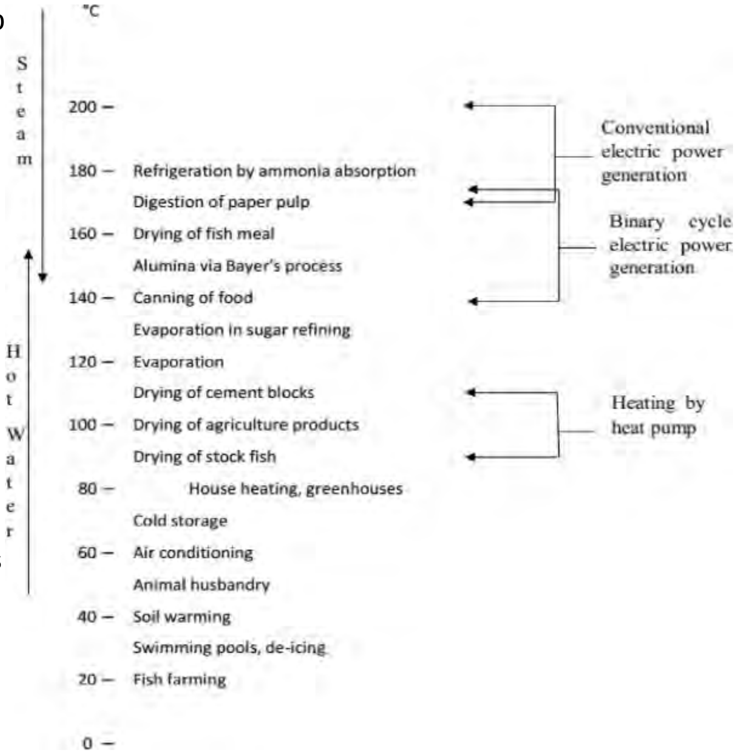

Figure 1: *Modified Lindal diagram for the classification of geothermal resources for various applications (Alhamid et al., 2016; Milenić et al., 2015).*

Weather Impacts on Cultivation In Iceland

Iceland straddles the boundary of subpolar oceanic (Köppen climate classification Cfc) and tundra (Köppen ET) zones, most similar in climate to coastal areas of southwestern Alaska, Kamchatka, and northwestern Norway. Winters are mild relative to the latitude (average Reykjavík January low -2,4°C / high 2.5°C), but long, dim (average Reykjavík January sunshine hours = 20), and subject to punishing waves of extratropical cyclones. Summers are very mild (average Reykjavík July low 8.8° / high 14.2°), calmer and drier (average Reykjavík December = 94.1mm / June 43.8mm). The low daily mean (Reykjavík = 4.7°) and cool summers create difficulty for cultivation due to low soil temperatures, despite otherwise favorable conditions like abundant summer sunlight (average Reykjavík May sunshine hours = 201) [Veðurstofan 2020a].

Thermal Resources

High-grade thermal resources are widely utilized in industry, particularly power generation. The importance of high temperatures can be seen in Carnot’s theorem, where the maximum efficiency in which work can be extracted is given by:

$$\eta_{\text{max}} = 1 - \frac{T_{\text{C}}}{T_{\text{H}}}$$

… where T_H is the temperature of the hot input reservoir and T_C is the temperature of the cold output reservoir, in Kelvins. As T_H converges toward T_C, the maximum theoretical efficiency for work extraction drops. Additionally, real-world efficiencies decline faster than Carnot’s theorem alone would suggest , while simultaneously, the amount of heat energy per litre of working fluid declines. These factors combine to rapidly render further extraction of work from the heat source (such as electricity generation) economically impractical at below ~80°C (Ahmadi et al 2020).

Mid-grade thermal resources, such as wastewater from electricity generation (or additionally in the case of Iceland, from more abundant, lower-grade geothermal resources) can still be utilized for heating. In the case of Iceland, municipal heat distribution systems are common in populated areas, with system feed-in temperatures around 80°C, declining temperatures within heating systems, and variable output temperatures – usually around 30-35°C (Veitur, personal communication). The lower bound again defines a zone of economic impracticality; heat transfer rates range from linear with respect to a temperature differential (conduction), to a difference in quadratics (radiation). As the difference in temperature between the hot water and the target being heated declines, so does the rate of heat transfer, eventually rendering attempts to further extract more heat from the system impractical.

The low-grade thermal water output that remains still has significant energy and is present in abundance, yet is of little utility. As an example, it can be blended with incoming mid-grade water resources that are above the target distribution temperature, and while this is done to some extent, most of the low-grade water in Iceland at present is simply discharged into rivers and/or the sea. As an example, in Reykjavík, a conduit containing an average of 75 l/s of water (over 100 l/s in the winter) at 29° flows along the north side of Stekkjarbakki, enters the stormwater system and is discharged (Veitur, personal communication).

Soil Heat

The activity of roots, and their microbial and mycorrhizal associations, is highly dependent on soil temperature (Hurd & Graves 1985), impacting growth (*Fig. 2*). Insufficient soil temperatures reduce water and mineral uptake. Iceland's soil on particular is defined by a distinctly cool year-round temperature profile. At the ForHot research site, a linear 15.6 ± 4.7 d/°C correlation was established between the length of the growing

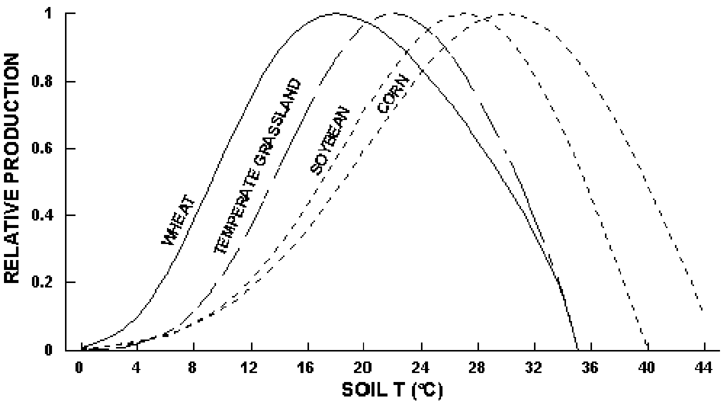

Figure 2: *The impact of soil temperature on growth of various plants. Reproduced from the CENTURY Soil Organic Matter Model.*

season and changes in soil temperature (*Leblans 2016*) - implying that just a few degrees of warming could potentially allow for the planting an entire additional short-season crop.

The traditional approach for extending the growing season in Iceland is the construction of greenhouses, which are abundant throughout populated areas of the country. However, greenhouse construction is an expensive endeavour, costing hundreds of euros per square meter. While greenhouses offer a number of significant advantages, including shelter, exclusion of wild pests, and most critically, a temperate climate, they additionally bring disadvantages, including reduced light, irrigation requirements, pollinator exclusion, sheltering of greenhouse pests, limited maximum roof heights, inaccessibility to heavy machinery, and structural maintenance. They can also be undesirable in an urban setting.

Few examples of heating the ground outdoors are recognized. In Iceland, the most notable example is potato and carrot cultivation at Auðsholt. A remote location with shallow (60m) borehole access to hot water, they utilize this stranded resource to heat one of their beds, yielding them an extended harvest. Their net annual yield of carrots, 200 tonnes, is considered to be significantly above that of the average farmer (SMH 2020). The heated bed uses no surface insulation, but row covers are used to prevent frost damage, which has the side effect of reducing soil heat loss through limiting convection and clear-sky radiation.

While many plants can tolerate hard freezes in their aboveground portions, plants generally exhibit significantly reduced root activity at low temperatures and cease growth in frozen soil. It has been demonstrated that the use of mid-grade geothermal water can yield to significantly increased yields (*Dell et al. 2013*) and extension of the growing season (*Guðni & Svavar 2018*). For example, Dell et al. describes two experiments - one (Landbúnaðurháskóli Íslands - LBHÍ) using 40-65° water/ethanol coolant with a dT of 10-15° and a flow rate of 10l/m in a 50m² bed; and the other (Keilir Institute of Technology - KIT) with 40° and 60° water in separate loops, also with a dT of 10-15°, and a flow rate of 4-8l/m per loop, each covering half of a 96m² bed. With this, they managed to achieve (vs. unheated controls):

- Tomatoes:
    - Spread: +87% (vs. -17%)
    - Stem diameter: +>100% (vs. +43%)
    - Harvest: First outdoor tomatoes in Iceland (vs. none)
- Zucchini:
    - Spread: +4% (vs. 100% death rate)
    - Stem diameter: +83% (vs. +2%)
    - Harvest: 4.6kg in 8 fruits (vs. none)
- Banana: Survived to the first frost (vs. a dead stalk)
- Strawberries (KIT):
    - # of stems: +118% (60°C), +80.6% (40°C), +28% (control)
    - Spread: +29% (60°C), +9% (40°C), -17% (control)

While certain places can indeed get mid-grade hot water for free (the KIT garden received it as discharge from a swimming pool's heat exchanger), in general such water in Iceland is in significant demand for municipal heating. The utility Veitur at present charges:

- **Residential**: 134.60kr/m³ (€0.83/m³), w/VAT
- **Rural**: 177,64kr/m³ (€1.10/m³), w/VAT
- **Pools (low-priority water)**: 67.28kr/m³ (€0.42/m³), w/VAT[1].

Assuming the latter (discounted) pricing, heating a hectare for a year at the rate of the above KIT garden would cost 22.6M kr (€138k) - a very hefty sum. Lower-priced resources, such as low-grade wastewater, would be required for a more affordable cultivation processes.

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[1] https://www.veitur.is/verdskrar/hitaveita

Insulation

In a uniform bed with no flow-rate limitations at the heat source (e.g., buried pipes) and heat sink (e.g., the air), there will be a linear temperature gradient between the source and sink (e.g. *dT/dx* in Fourier's Law). At any given height, the temperature of the soil will thus be directly dependent on the temperature of the heat source. Using a low-grade heat source such as geothermal water will thus create significantly lower soil temperatures at any given depth than using high-grade heat.

The standard way to trap heat within a given volume is with insulation; however plants generally grow poorly in insulating materials. Consequently, a design of alternating ridges of soil and insulation needs to be investigated.

Any choice of insulation material must be acceptable with regards to a number of parameters. It must have as low of a thermal conductivity as possible. It must be low cost and readily available. It should not be harmful to the plants. It must be compatible with lying exposed in an outdoor environment. And lastly, it must be as environmentally-friendly as possible. With regards to these parameters, two options were considered.

Wood Mulch

As an island with a significant imbalance between imports and exports, Iceland tends to accumulate a significant excess of wood shipping pallets. Scrap timber is also a common byproduct of the construction industry. Dry wood mulch has a thermal conductivity of 0.08-0.14W/m-K, but in wet state is significantly higher (~0.3W/m-K) (Skogsberg & Lundberg 2005).

Pumice

Iceland has extensive deposits of pumice from modern rhyolitic eruptions (as well as scoria from basaltic eruptions). A low density, highly porous mineral, pumice is mined from near Mt. Hekla and exported by Jarðefnaiðnaður (JEI) for use in construction, biotech, hydroponic farming, and as a lightweight aerating soil additive. Its bulk thermal conductivity is reported by JEI as 0.08-0.12 W/m-K [2], similar to dry wood mulch. Normal pricing is 8000 kr/m³ (~€50/m³) w/VAT for grey pumice and 10000 kr/m³ (~€60/m³) w/VAT for white; there is no thermal conductivity difference between the two.

Soil

Iceland is dominated by andosols - estimated at potentially >5% of the total world's andosol distribution - of an unusual formation variety (Arnalds 2004). Subglacial eruptions form a fine dust, which is carried out into the highlands by sediment-rich subglacial rivers and outburst floods. Aeolian deposition then deposits it across the country at rates ranging from 0.01 to 1mm per year. In areas with low rates of organic material deposition, it can build up into thick layers of phosphorus-binding *jöklaleir* ("glacial clay") which most plants have difficulty growing in. Rich in allophane spherules, the highly-absorbent clay also limits water availability to roots and has little cohesion.

As such a clay-rich site, in addition to having to reinforce the ground to support trucks, it will be necessary for us to import an appropriate growing medium.

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[2] https://jei.is/technical-data.html

Materials and Methods

Type of Research

The research is a comparative study, mainly quantitative focusing on variables that are measurable even though qualitative method is used to evaluate plants health conditions.

This study examines the potential for the use of low-grade warm water - a common low-value waste product - to expand cultivation possibilities instead of mid-grade water resources. To compensate for the lower rates of heat transfer and the lower heat content of the water, two low-cost, environmentally-compatible insulation materials (pumice vs. wood mulch from scrap timber) are tested in order to reduce the rate of heat transfer to the surface.

Environmental Factors

A number of different external factors can affect the plants apart from the soil, including:

- Temperature
- Wind
- Sunlight
- Precipitation

These factors were monitored so that they could be controlled for if needed. The layout of the study site on these factors was also considered.

Study Area

The garden plot fits into an approximately 20m bounding square in a clearing in a sparse woods north of Stekkjarbakki and west of the community garden. (Fig. 3)

__Figure 3__: Aerial view showing the location of the research garden, north of Stekkjarbakki.

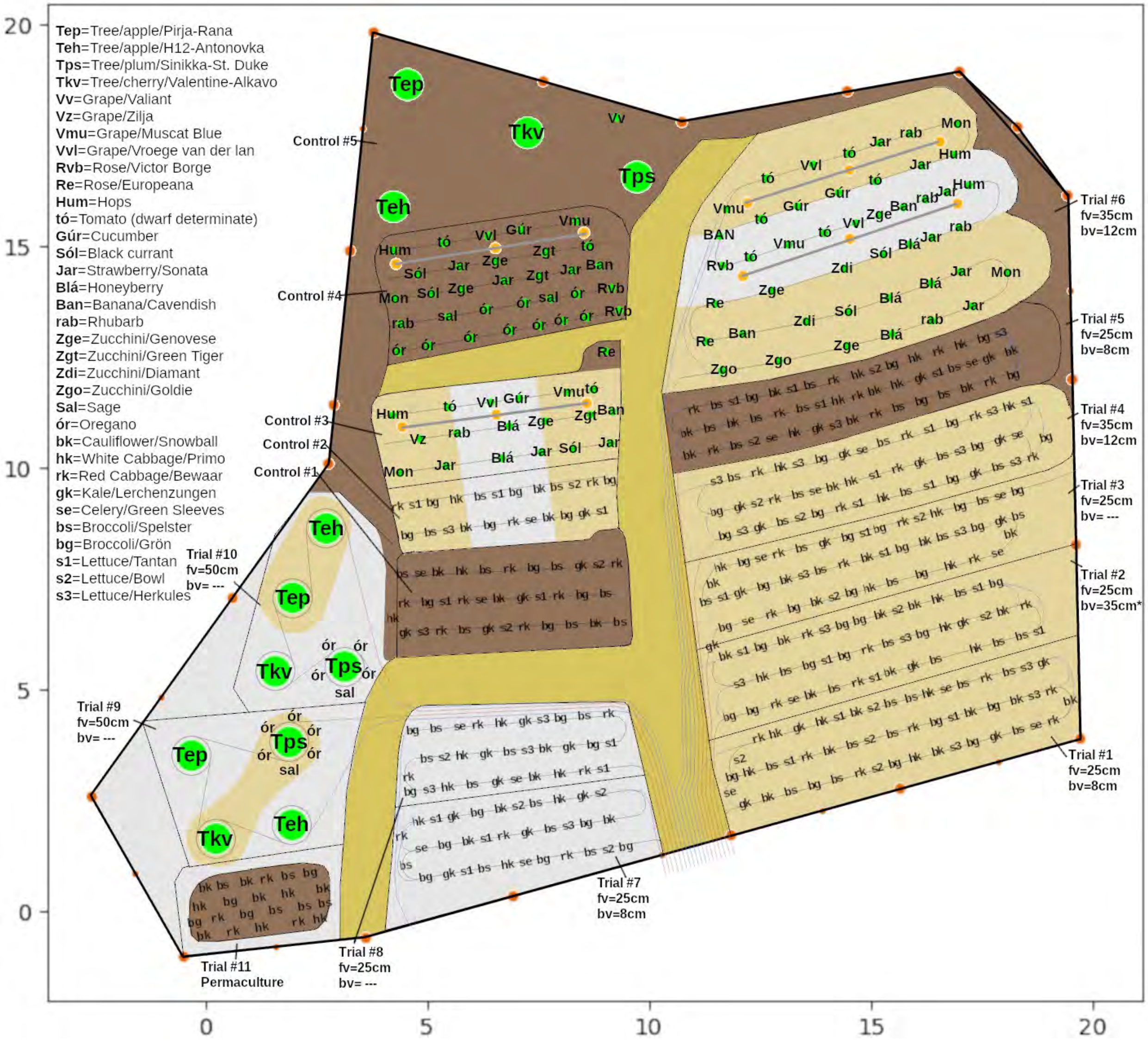


Figure 4: Map of the ALDIN research garden

Perimeter fencing was constructed to enclose approximately 250m² of space, as a precaution against the abundant local rabbits, with the base trenched into the ground (*Fig. 6*). Mulch paths (gold) were laid, bisecting the beds (tan = mulch; grey = pumice; brown = soil). For the diversity experiments, a series of trellises were constructed with fenceposts and horticultural twine for climbing plants (*Fig. 5*). Though extensive amounts of material were added to the garden, no attempts were made to level it; the east-northeast quadrant slopes slightly (~5°) toward the east trees.

Figure 5: *Experiment #6 before the first frost*

Figure 6: *Setting the posts for the rabbit fencing.*

Laying And Plumbing The Heating System

Low-grade geothermal water arrives from Stekkjarbakki and is fed into a valve cabinet (Fig. 7). Outflows (*fv*) flow into each experiment, while backflows (*bv*) return to the cabinet with temperature meters, before being discharged to the east. Two experiments lack backflow, and are fed straight to discharge; each has their own meter at the point of leaving the experiment. Backflow valves are adjusted so all outflow temperatures are identical. Individual experiments can be disabled without affecting overall settings via the inflow valves.

Figure 7: *A cabinet built by Arnar Pétursson houses the valve assembly. Pumice was later added at the base.*

Backflow slowly runs through a trench before entering a drainage channel into the valley, to allow it to cool to ambient temperatures and avoid thermal pollution.

Figure 8: *Laying the PEX piping*

Heating pipe is 25mm PEX normally used for snow-melting systems with mid-grade (~55°) water. Due to delays in getting a hot water connection, the pipe had to be laid cold, which made it very difficult to bend. Digging, laying, and securing the pipe proved to be a highly labour-intensive task, and additional labour was brought in to assist. Trenches had to be left behind in order to be filled with insulating material between the pipes. Tree plantings were given two loops of heating pipe around their bases Control beds were given no heat pipes.

One additional “permaculture bed”, to utilize compost heat, was formed by layering (bottom to top): A) garden waste; B) rotting branches; C) turf; and D) soil.

Left to right: 1) garden waste laid down; 2) branches laid atop it; 3) turf laid atop the branches; 4) topped with soil

Overview of the Experimental Beds

The beds in the experiment are:

Name	Insulation	Inflow Depth (cm)	Outflow Depth (cm)	Outflow Position	Trench Depth (cm)	Row Spacing (cm)	Description
Experiment 1	Mulch	25	8	Above	30	60	Common
Experiment 2	Mulch	25	35	Between	30	60	Common
Experiment 3	Mulch	25	---	---	30	60	Common
Experiment 4	Mulch	35	12	Above	30	60	Common
Experiment 5	None	25	25	Between	---	60	Common
Experiment 6	Both	35	12	Above	40	80	Diverse
Experiment 7	Pumice	25	8	Above	30	60	Common
Experiment 8	Pumice	25	---	---	30	60	Common
Experiment 9	Both	50	25	Spiral	---	---	Trees
Experiment 10	Both	50	25	Spiral	---	---	Trees
Experiment 11	None	---	---	---	30	60	Permaculture
Control 1	None	---	---	---	---	60	Common
Control 2	Both	---	---	---	30	60	Common
Control 3	Both	---	---	---	40	80	Diverse
Control 4	None	---	---	---	---	60	Diverse
Control 5	None	---	---	---	---	---	Trees

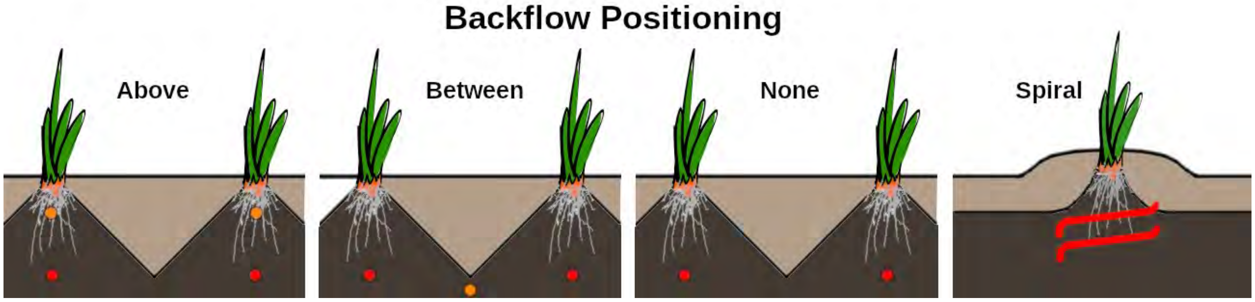


***Figure 9**: Various backflow configurations used in the different beds*

Outflow can be:

- **Above**: The outflow pipe is positioned directly above the inflow pipe, so that the cooler water exchanges heat with the cold surface rather than the warmer, deeper inflow water. 8cm was more difficult to keep in position inside the rows without causing soil collapse into the trenches vs. 12cm.

- **Between**: The outflow pipe is shallowly buried at the bottom of the trenches, to shield against heat loss to the ground.
- **None (---)**: After a single pass through the system, outflow immediately exits the experiment without returning.
- **Spiral**: Used around trees; water enters, does approximately two loops around the tree, then leaves towards the next tree.

In the “Description” column, the following terms are used:

- **Common**: Approximately the same mix of brassicas, celery, and lettuce varieties.
- **Diverse**: A wide range of plants, some of which have poor hardiness, and none of which are common enough to achieve statistical significance, in order to gain diverse experience / anecdotal evidence for further study.
- **Trees**: Four trees in each experiment, one of each type. In the experimental beds, two use wood mulch and two use pumice. The two experimental beds are identical except for which trees have mulch and which have pumice; however, during the winter, one will be set to a significantly colder temperature than the other to examine impacts on hibernation.
- **Permaculture**: Soil over a compost bed, as described earlier.

Shade at the Experimental Site

As a clearing in a forest, light levels cannot be assumed to be constant at all locations in the experiment. Consequently, it was decided to create shade maps of the area at both the beginning and the end of the experiment, each at different times of day. These will need to be summed, weighed by timespan, gaussian-averaged, and broken into lighting zones, in order to account for the impact of light on growth.

Balancing Heat Flow

After heat was connected on 27 August, flow between experiments was incrementally balanced over the first week, with overall flow rates controlled by the master valve. Higher flow rates were used initially (up to 24 l/min) due to the cold soil, and steadily reduced to 10.4 l/min by 1 september. However, continuous monitoring of the inflow temperature showed that water was not arriving at anywhere near the expected 35° as expected by Veitur, but rather around 28°. To compensate for the lower peak temperatures, it was decided to target higher outflow temperatures, which required a higher flow rate of around 16 l/min.

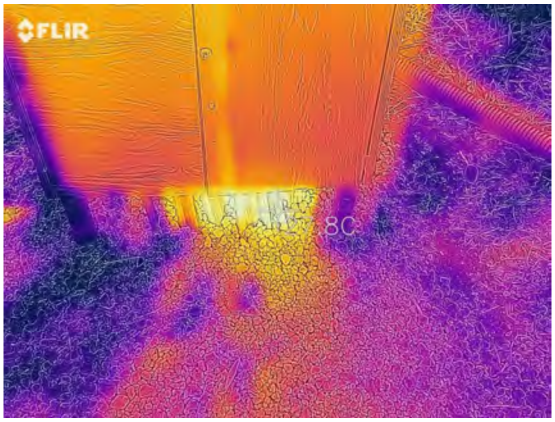


Figure 10: *Hot water descends from the cabinet into loose pumice*

Monitoring Heat Flow

Heat flow was monitored by imaging with a FLIR ONE camera. Such monitoring had to be done at night, as even the impacts of light from a cloudy day had the effect of drowning out the infrared signal from the soil.

Areas where insulation was unintentionally poor became immediately clear, as did the overall paths of the plumbing in the soil (*Fig. 11*). Heat flow through mulch was more visible through the soil than heating through pumice. By contrast, experiments that lacked near-surface backflow paths were less visible and distinct.

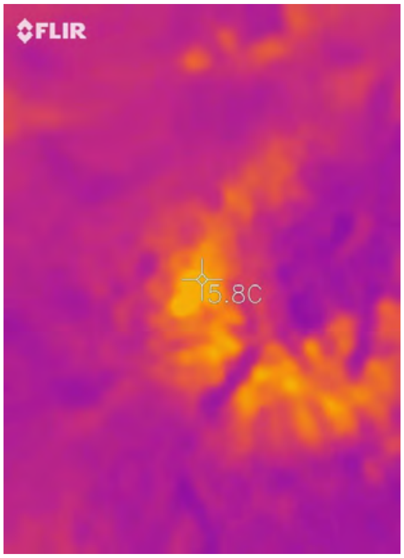


Figure 11: *A section of poor insulation in experiment #8, discovered by IR*

In order to gain a clearer picture of the overall heatflow to the surface, numerous infrared images were captured from the southwest, southeast, and northeast corners while standing on a ladder, then stitched together into panoramas with Hugin, using manual control points (*Fig. 12*).

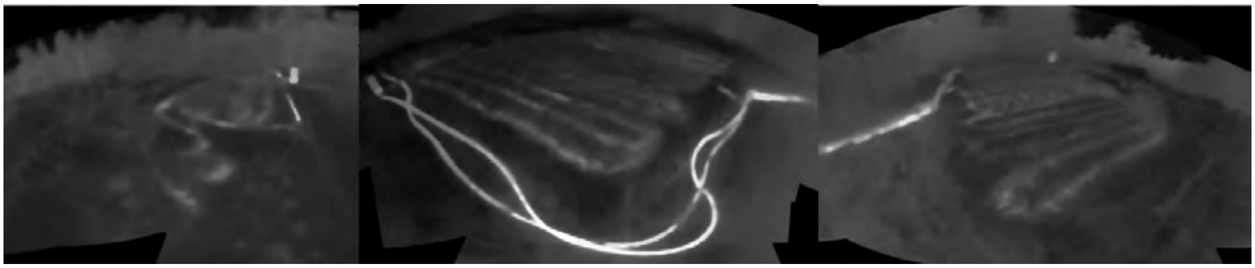


Figure 12: *Left to right: southwest, southeast, northeast. Illumination balance should not be considered as constant between images*

A series of temperature measurements were additionally taken with a pair of 40cm analog compost thermometers between 30 September and 5 October, in relatively steady weather conditions. Measurements were targeted at 6, 12, 25, and 40cm; however, in some places, a layer of drainage gravel was struck and could not be penetrated further.

Insulation

Insulation is arranged in an alternating series of ridges of soil and insulation, to achieve the effect in the Fig. 13:

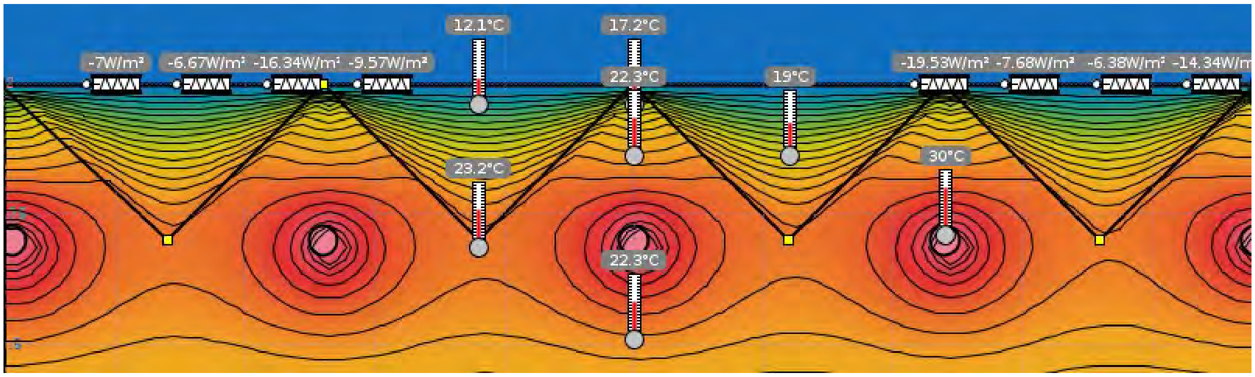


Figure 13: *Simulation of a garden cross section (no backflow, 60cm row spacing, 30cm depth) in Energy2D*

Wood Mulch

For the project, mulch was acquired in three truckloads from Sorpa, a municipal waste handler. Sorpa was supportive of the research and provided it at no cost (excepting transport). The first truckload was laid out to build a biodegradable road for further trucks to reach the garden site. The second load (*Fig. 14*) was of a different material, old half-rotten branches of uneven sizes and with a significant content of inorganic scrap, and was unsuited for purpose. The third load was the same as the original material and was utilized for the garden (*Fig. 15*).

Figure 14: *Second load of wood mulch*

The mulch consists of (predominantly, but not entirely) unpainted chunks of wood generally ranging from 3-12cm on their long axis and usually about three times as long as they are wide. Some finer wood debris was present as well. All mulch contained some content of inorganic scrap - bits of plastic, string, nails, brackets, etc. In large scale operations, much of the material could be easily removed by automated sorting systems, but for our needs it was removed by hand, and presented only a minor inconvenience to the task.

Figure 15: *After distributing the mulch.*

Pumice

As with Sorpa, JEI kindly donated a truckload of white pumice to us at no cost except transport. The pumice is of superb aesthetic appearance, reminiscent of a Japanese garden.

Soil

The company Gæðamold provided two trucks of mix of crushed shell sand and aged compost (sold likewise under the brand name “gæðamold”) at a discounted rate. This high-carbon / high-calcium mix (*Fig. 16*) is commonly used to good results in local gardens. Initial calculations suggested that only a single truckload would be needed to achieve our 30cm depth target, but the material compacted down heavily during garden construction, even with deliberate efforts to avoid compaction of cultivated areas. In a portion of the plot (spanning both control and experimental beds), 30cm of drainage gravel already on site was spread out before laying down the soil (*Fig. 17*).

Figure 16: *Gæðamold*

Figure 17: *Already-present drainage gravel was spread before soil could be laid down.*

Plants

Most plants were supplied by Jón Guðmundsson, a local horticulture expert. For most beds, a mixture of the following frost-resistant traditional Icelandic garden plants were planted out. Including their id codes (in brackets), these are:

- *[bg]* Broccoli “Grön” (tall and lanky at the time of planting)
- *[bs]* Broccoli “Selster”
- *[hk]* White cabbage “Primo”
- *[rk]* Red cabbage “Bewaar”
- *[bk]* Cauliflower “Snowball”
- *[gk]* Green kale “Lerchenzungen”

- *[se]* Celery “Green Sleeves”
- *[s1]* Lettuce “Tantan”
- *[s2]* Lettuce “Bowl”
- *[s3]* Lettuce “Herkules”

For each of the tree experiments, one of each of the following trees was planted:

- *[Teh]* Apple “Heyer 12” / “Antonovka”
- *[Tep]* Apple “Pirja” / “Rana”
- *[Tkv]* Cherry “Valentine” / “Alkavo” (2x) - “Colt” (1x) (*Fig. 18*)
- *[Tps]* Plum “Sinikka” / “St. Duke”

Figure 18: *Cherry 'Valentine'*

These are all hardy cultivars which can, with sufficient shelter, survive and fruit in the Icelandic lowlands.

For the diversity experiments, the following plants were provided:

- *[Vv]* Grape “Valiant” (hardy variety)
- *[Vz]* Grape “Zilja” (hardy variety)
- *[Zge]* Zucchini “Genovese”
- *[Zdi]* Zucchini “Diamant”
- *[Zgo]* Zucchini “Goldie” (*Fig. 19*)
- *[Zgt]* Zucchini “Green Tiger”
- *[sal]* Sage
- *[ór]* Oregano

Figure 19: *Zucchini 'Goldie'*

The following additional plants were purchased from Flóra nursery in Hveragerði:

- *[Rvb]* Rose “Victor Borge”
- *[Re]* Rose “Europeana” (*Fig. 20*)
- *[Hum]* Hops

- *[tó]* Tomato (dwarf determinate)
- *[Gúr]* Cucumber
- *[Sól]* Blackcurrant
- *[blá]* Honeyberry
- *[Ban]* Banana “Cavendish”
- *[Vmb]* Grape “Muscat Blue”
- *[Vvl]* Grape “Vroege van der Laan”
- *[rab]* Rhubarb
- *[jar]* Strawberry “Sonata”

Figure 20: *Rose "Europeana"*

The following were provided by the author, after soil heating commenced:

- *[Mon] Monstera deliciosa*
- *[BAN]* Banana “Jamaican Red”

Growth Measures

It was decided that plants in the experiment would be measured by stem diameter (thickest point, except in celery, which would be measured ¼ up the thickest stalk; unmeasured in lettuce), plant height, plant length (longest axis), and plant width (90° cross axis). An additional measurement (stem height) was taken but rejected for inconsistency and unclear utility. The produce of plants was additionally measured where present, including count, width (of the widest one, *Fig. 21*), height (of the same one), and in the case of harvest, number, width, length, and mass.

Figure 21: Measurement of produce width

The diversity experiments do not include enough statistically-significant datapoints and are thus excluded. The permaculture experiment, due to its late planting dwarfing its plants, is likewise excluded.

A formula was developed in order to evaluate the growth of the plants:

$$L + W + H + (L*W)^{0.5} + (L*H)^{0.5} + (W*H)^{0.5} + (L*W*H)^{1/3} + (H*D^{2}*2)^{1/3}*C + G1/6 + G2/7 + G3/8 + G4/9 + G5/10 + G6/11 + G7/10 + G8/11 + G9/12$$

Where:

- L is the plant’s length (long axis, cm)
- W is the plant’s width (90° cross axis, cm)
- H is the plant’s height (3cm added for insulated experiments due to measurements happening from the surface of the insulation but the plants being buried approximately 3cm deep)
- D is the diameter of the stalk (mm)
- C is *0* for cauliflower and white cabbage (which have inconsistent, unreliable, often missing stalk diameters), and *1* for all other crops. C is effectively zero for lettuce, since it was unmeasured.
- G1 is the cumulative harvest up to 27 September, in grams
- G2-9 are the harvests on each respective following visited day, in grams.

The formula was designed to avoid overweighing any single parameter or group of parameters, which might be skewed by the pattern in which a particular plant grew. It can be broken down into its individual components:

- **$L + W + H$** – Each axis is evaluated independently and weighed equally and linearly.
- **$(L*W)^{0.5} + (L*H)^{0.5} + (W*H)^{0.5}$** – Each cross section is evaluated and summed. Since cross sections grow quadratically with respect to their parameters, the sum is of their square roots.
- **$(L*W*H)^{1/3}$** – The net volume of the plant’s bounding box. Since volumes grow in a cubic manner with respect to their parameters, the cube root is used.

- ***$(H*D^{2}*2)^\wedge⅓*C$*** – Height times stalk diameter squared is linearly proportional to the volume of the stalk. This is complicated by taper, and should be weighted significantly more than overall plant volume due to it being a solid mass rather than primarily open space. Consequently, an experimentally derived parameter (2) was discovered to avoid overweighing this component. As it is a volumetric measure, its cube root is utilized.
- ***G1/6 + G2/7 + G3/8 + G4/9 + G5/10 + G6/11 + G7/10 + G8/11 + G9/12*** – All of the harvests leading up to the point of measurement should of course be considered in the yield (G1). The question then comes, what to do about harvests that are ready shortly thereafter? They still represent produce, but should be discounted by the fact that they were not ready for harvest at the time of measurement. Consequently, weighing factors (the divisors) must be derived experimentally to prevent overweighting of these parameters relative to others.

Two time periods were considered: from planting to the first field measurement, and from there to the final field measurement. The change between the measures was considered both additively (+), i.e. a linear difference between the latter value and the former; and multiplicatively (*), i.e. the latter value divided by the former. Since each variety of plant has different growth properties, the averages for each plant variety were measured and used to normalize between species.

Results

Timeline

- **28 April:** Discussions with the city begin.
- **4 May**: Applied for funds to complete the project.
- **9 June**: NSN grant approved.
- **15 June:** First contacted Veitur.
- **16 July**: Received final go-ahead from Reykjavík. Materials immediately ordered.
- **17 July**: Mulch road to the site constructed.
- **21 July**: First load of soil arrives.
- **23 July**: Pipes installed in the ground.
- **24 July**: Rotten branches arrive and are rejected. Plants arrive from Jón.
- **25 July**: Rabbit fence built, first “good mulch” applied (east half), trees planted.
- **26 July**: Plants purchased from Flóra.
- **27 July**: Mulched beds (east side) planted.
- **28-29 July**: Remaining beds (except permaculture) planted.
- **1 August**: Trellises completed.
- **14 August**: Contract with Veitur completed and signed.
- **23 August**: Trenching for the connection from Veitur completed.
- **25 August**: Permaculture bed planted. First measurements start.
- **27 August**: Warm water connected.
- **29 August**: Monsteras and large banana planted.
- **30 August**: First storm, above freezing; minimal damage.
- **2 September**: First measurements completed.
- **5 September**: Second storm. Winds from the north, below freezing. Significant damage.
- **6 September**: Leg injury forces a hospital visit; reduced activity over the coming days.
- **12 September**: Second measurements started. This document started.
- **27 September**: Second measurements completed. Infrared images completed.
- **8 October:** Contract with Veitur is re-reviewed.
- **12 October**: First draft completed.
- **21 October**: Final draft completed.

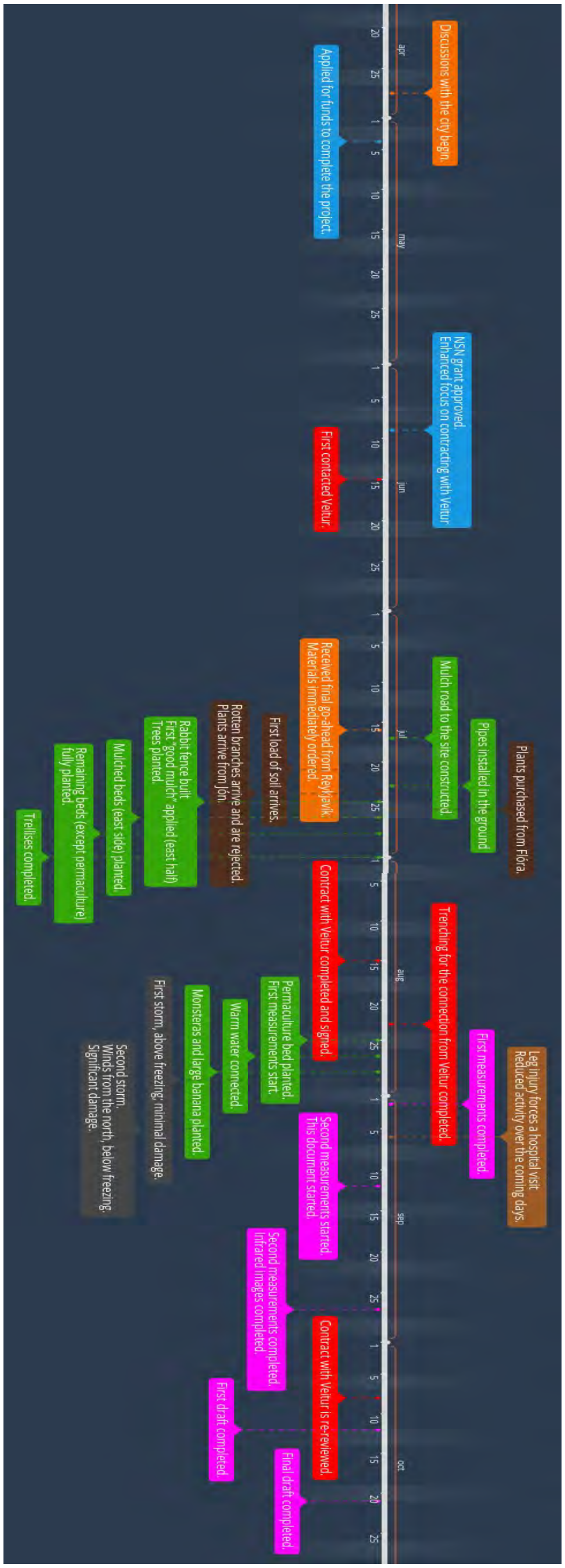


Figure 22: *ALDIN research garden development timeline*

Weather

August temperatures matched the 2010-2019 trend, but was 0.9°C warmer than the 1961-1990 trend. Rain was 50% more than the 1961-1990 trend, and rain days were 16 instead of 12. Sunshine hours were 141.5, vs. the 1961-1990 average of 154.8. Wind was average [Veðurstofan 2020b].

September temperatures were 1.4°C lower than the 2010-2019 trend, but avereage for the 1961-1990 trend. Rain was 60% more than the 1961-1990 trend, and rain days were 19 instead of 12. Sunshine hours were 110.1, vs. the 1961-1990 average of 124.8. Wind was 0.6m/s above average [Veðurstofan 2020c].

In summary:

- Temperatures were roughly average
- Precipitation was more than average (but we anticipated irrigating during dry periods regardless)
- Sunshine was below average
- Wind was around average to slightly above average

No need was seen to control for atypical conditions, although it should be noted that in a regular year drier periods would be expected (potentially harmful if no irrigation is used), but also would receive more sunlight (something already deficient in our garden site).

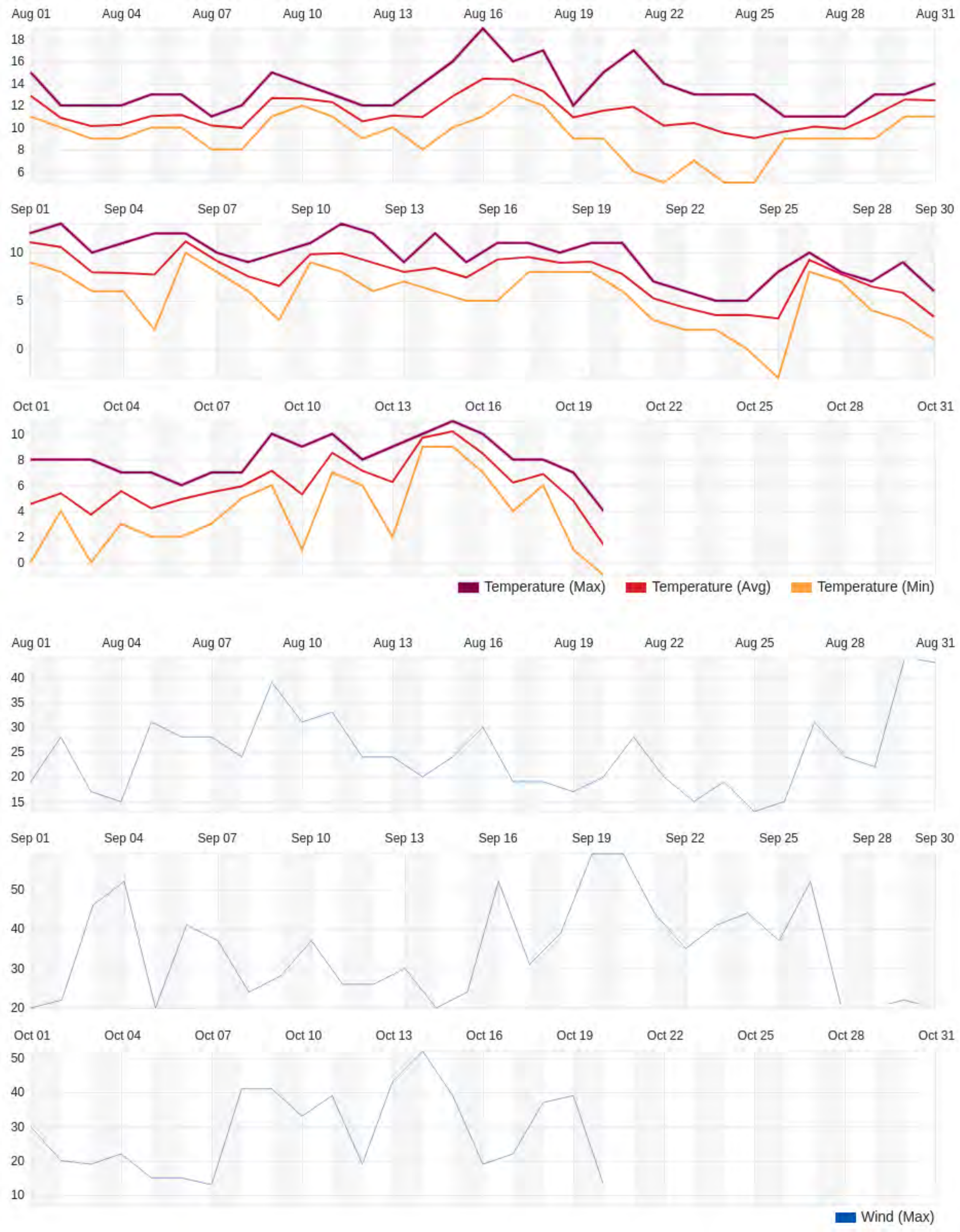


***Figure 23**: Weather trends at BIRK/Reykjavik, provided by WeatherUnderground.com.*

Shade and Sunlight

Shade maps were made of the area, each over the course of roughly a week over two separate timeperiods.

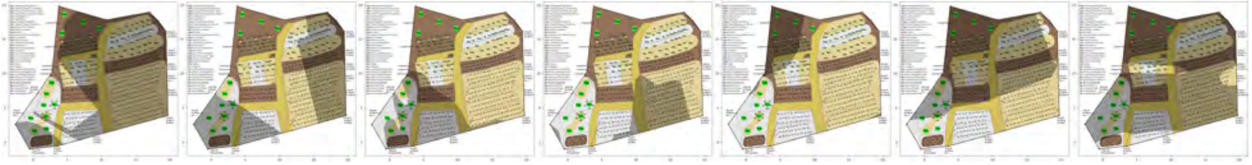


Figure 24: *Sample shade maps at made at different times of day during the course of the experiment.*

As per the experiment design, these were unified (weighted by timespan), gaussian-averaged, and broken into ten separate lighting zones (*Fig. 24*).

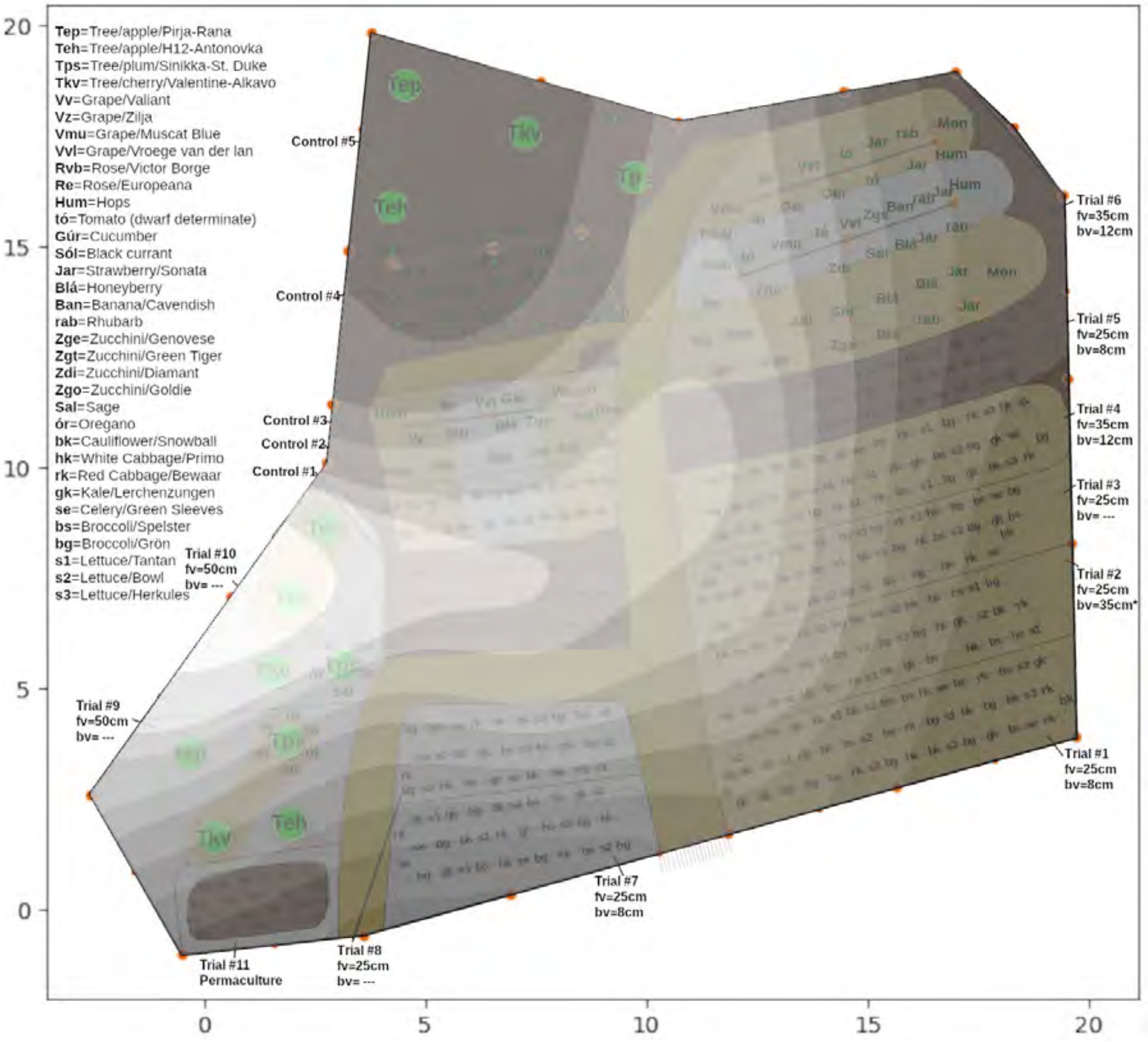


Figure 25: *The lighting zones within the ALDIN research garden.*

It becomes immediately clear that, unfortunately, by and large the control beds were in sunnier locations than most of the experimental beds. In particular, the southeast corner of the garden is particularly shady. Controlling for shade levels consequently was deemed necessary as part of the experiment.

Insulation

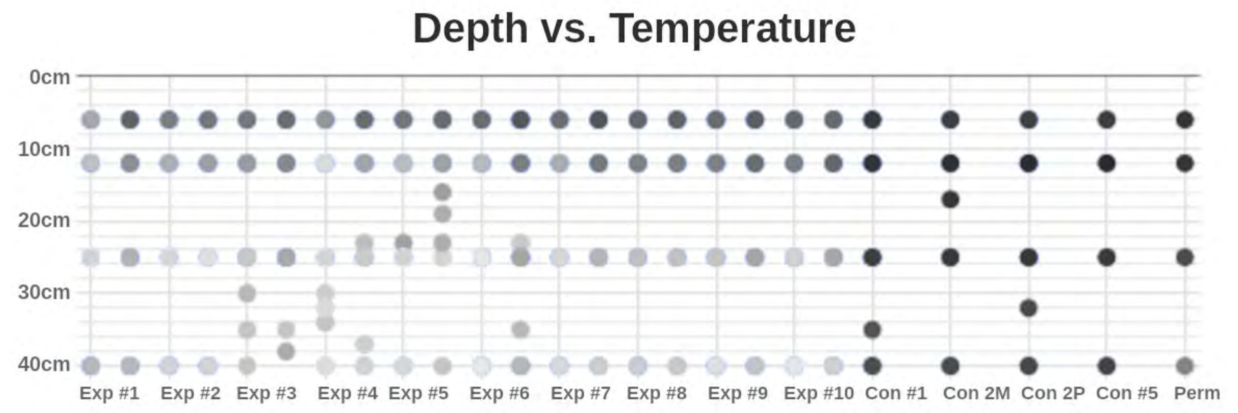
Wood Mulch

The mulch provided a good aesthetic appearance, although of inferior aesthetic quality to decorative bark mulch. It demonstrated a good but limited control of garden weeds; its high moisture levels still allowed some weed growth. As it is organic, it will rot over time, and the rate of replacement and any challenges to maintaining the insulative properties of the beds will require future research. It has proven relatively resistant to compaction from foot traffic. It remained in a nearly constant moist state, which would be suggest a higher (~0.3W/m-K) thermal conductivity. A significant problem with slugs was observed in mulched areas, particularly in shady edges.

Pumice

It has proven excellent at controlling weeds. An inorganic material which will not rot, foot traffic still poses the potential to slowly wear it down, and repeated plantings may work it into the soil; we intend to monitor this over time. It can also blow away at more exposed sites in intense Icelandic winds, although in the presence of garden crops and surrounding trees, we have not experienced this to any visible extent. Its resistance to foot traffic proved sufficient for walking, but not as significant as the mulch. In the field it did not saturate as heavily as wood mulch and dried out much faster. It additionally proved significantly more resistant to snail traffic than the wood mulch.

In-Situ Temperature Measurements



	L	6cm	12cm	---	25cm	---	40cm
Exp #1	**Pipes**	18.5°, 19.75°, 11.75°, 13°	18.8°, 22°, 25.25°, 16°		17.8°, 24.25°, 25.25°, 18.5°		16°, 21.5°, 17.5°, 17.5°
	Between	12°, 12.25°, 8.75°, 8.5°	13°, 13.25°, 14°, 15.25°		16.5°, 17.25°, 16°, 16.5°		16.75°, 18.5°, 16.5°, 16.5°
Exp #2	**Pipes**	12.75°, 13°, 12.25°, 12°	16°, 17.8°, 19.25°, 15.25°		22.5°, 25°, 19.75°, 20.5°		21.5°, 18°, 17.5°, 18.75°
	Between	12.75°, 13°, 12.25°, 14.5°	15°, 16.5°, 15.75°, 14.5°		22.75°, 19.75°, 18.5°, 18.5°		20.5°, 23°, 18°, 18.75°
Exp #3	**Pipes**	11.5°, 12.5°, 12.25°, 12°	15°, 15°, 16°, 13°		19.25°, 18°, 18.5°*, 17.5°		18°, 18°, ---, 17°
	Between	10°, 11.25°, 12°, 11.25°	13.25°, 13°, 13.75°, 13.5°		17°, 15°, 15.25°*, 16.25°*	18°@35cm, 16°@38cm	18°, ---, ---, ---
Exp #4	**Pipes**	13°, 16.5°, 16°, 11.75°	18.25°, 19°, 16°, 18.25°		20.25°, 23.25°, 23°, 23.5°	18°@34cm, 18.5°@30cm, 21°@32cm	19.75°, ---, ---, ---
	Between	9.75°, 16°, 8.5°, 10.5°	15°, 18.75°, 14°, 14.25°	17.25°@23cm	17.75°, 19.75°, ---, 18°	18.75°@37cm	18.25°, 19.75°, ---, ---
Exp #5	**Pipes**	11°, 12°, 12.25°, 12.5°	14°, 17.5°, 18°, 20°	15.25°@23cm	---, 21°, 23°*, 19.5°		---, 20°, ---, 18.75°
	Between	11°, 12.5°, 11°, 10.25°	13.5°, 17.5°, 16.75°, 13.5°	16.25°@19cm, 19.5°@23cm, 15°@16cm	---, 19°, ---, ---		---, 18°, ---, ---
Exp #6	**Pipes**	10.25°, 9.5°, 10°, 11.5°, 13.5°, 12°	16.5°, 14°, 17.5°, 16.75°, 18.5°, 19°		19°, 19°, 21.5°, 20°*, 22°, 21.75°		21.75°, 22.25°, 19°, ---, 22.25°, 18°
	Between	8.5°, 8°, 10°, 12.25°, 8°, 9.75°	13°, 11.75°, 12.5°, 15°, 10°, 13°	18.25°@23cm	16.25°, 11.75°, 12.5° ---, 13.75°, 17°		17°, 18°, 16.25°, ---, 16°, 17.5°
Exp #7	**Pipes**	11.75°, 12.75°, 10.25°, 10.5°	15°, 19.5°, 18.25°, 17.5°		20.25°, 24°, 17°, 23°		21°, 21.25°, 17.5°, 22°
	Between	9°, 9.5°, 7.5°, 9°	10°, 14.5°, 11.5°, 14°		16.5°, 17.5°, 17.5°, 18.5°		18.5°, 18.5°, 18.5°, 19.75°
Exp #8	**Pipes**	10.5°, 11.75°, 7.75°, 10.5°	12.75°, 13.5°, 11.5°, 13.5°		15.5°, 16.25°, 20.5°, 21.75°		19°, 16.25°, 20.5°, 18.25°
	Between	11.5°, 9.75°, 9.25°, 8.5°	11°, 12°, 12.5°, 9.5°		17.25°, 15.5°, 17.25°, 14.5°		18°, 18°, 18°, 15.75°
Exp #9 + 10 Mul.	**Pipes**	12.25°, 9.75°, 11.25°, 11°	15°, 12.25°, 12.75°, 11.25°		20.25°, 16.5°, 17.25°, 18°		20°, 18°, 19°, 23°
	Between	11.5°, 8°, 10.25°, 10.5°	12.5°, 10.75°, 11°, 10.25°		16°, 14.25°, 15.75°, 16.25°		17.5°, 16.5°, 18°, 19.5°
Exp #9 +	**Pipes**	11°, 10.5°, 11.25°, 10.5°	15.5°, 12.25°, 11°, 11.25°		22°, 17°, 18.25°, 18.75°		20°, 20.25°, 21.75°, 20°
	Between	11.5°, 11°,	12.5°, 9.5°,		16.5°, 13.5°,		19.5°, 17.25°,

10		11.25°, 10.25°	10.5°, 10.5°		15.5°, 17.5°		18.75°, 19.5°
Control #1		8.5°, 7.75°, 7°, 5.5°	7.75°, 6.75°, 7°, 6°		8.25°, 7.25°, 7.75°, 7.5°	8°@35cm	10.25°, 8°, 9.25°, ---
Control #2M		8°, 6.75°, 8.25°, 7.5°	7°, 5.5°, 7.25°, 6.25°	7°@17cm	7.5°, 6.5°, ---, 7.75°		8.5°, 9°, ---, 8.5°
Control #2V		8°, 9°, 7.5°, 6.75°	7°, 6°, 6.5°, 5.5°		7.75°, 7°, 7.5°, 6.5°	8.5°@32cm	9.25°, 8°, ---, 7.75°
Control #5		8°, 7°	6.75°, 5.5°		7.25°, 7.25°		8.25°, 8°
Permaculture		7°,	7°		8.75°		13°

Figure 26: *Depth vs. temperature. (*) indicates 'unable to penetrate further'. All measurements not at 6, 12, 25, or 40cm were additionally due to an inability to penetrate further.*

As all measurements were made during the daytime, the top measurements of control beds (6cm) were warmer than deeper measurements (>= 12cm). However, from 12cm, temperatures trended up with depth, corresponding to a warmer atmosphere earlier in the season.

The permaculture bed proved warmer than ambient but unable to create a large heat rise, with the temperature at 40cm at only 13°. Two possible reasons for this are an insufficiently “hot” compost (too much woody material, insufficient leafy material), and too rapid loss of heat to the surrounding cold soil. The turf overhead, on which the cultivation soil was spread, may function to insulate the bed from the warmth below.

Figure 27: *Compost thermometer*

All water-heated experimental beds were thoroughly warmed. This is not so much of an indicator of the effectiveness of the warming mechanism as it is of the fact that flow rates were adjusted so that all backflow arrived at the same temperature. There was a significant amount of variation between measurements - potentially in part due to different measurement locations, but likely in large part due to how close the probe ended up to the water pipes. Since measurements were made during the daytime, it was impossible to use infrared to locate the pipes beneath the soil.

Experiments #2, with backflow located at 35cm depth between rows, created a more even heating, apparently without sacrificing heating within the rows themselves. It's not clear if this would be the case if there had been a greater difference between inflow and backflow temperatures, as initially intended when inflow water was expected to be 35°.

Experiments #3 and #8, lacking backflow, showed opposite trends. Experiment #3 (mulch-insulated) showed great warmth at all depths. Experiment #8 (pumice-insulated), by contrast, showed less warming than its neighbor, #7. There was significant variation at depth in temperature measurements in #8, and it's possible that measurements simply happened to be poorly positioned.

Experiments #4 and #6, with the pipes laid deeper (35cm inflow, 12cm backflow), created greater heat at depth, apparently without sacrificing heat near the surface. There was a more amplified temperature difference between rows and the inter-row area in #6, due to the greater row spacing.

Experiment #5 (uninsulated) was unremarkable; heat distribution in the area around the piping was similar to other experiments, although the area between pipes was - as expected - more similar in temperature to that where the pipes are located.

Surface temperatures in pumice experiments were cooler than with mulch experiments - an effect that one would expect with a better insulator.

A key aspect of interest is the rate of heat loss between experiments. Flow rates and pressures were measured with the flow shut off to all experiments except for one, for each experiment. With 25mm pipes and low flow rates, the pressure drop should be overwhelmingly within the valves rather than the pipes, and thus the pressure drops within each experiment divided by the sum of all individual pressure drops should closely approximate the of the fraction of the flow in each respective experiment (*Fig. 27*).

	Closed	**Open**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**
Flow (l/min)	0	15.88	11.12	11.01	6.03	12.59	11.81	14.40	11.06	8.30	9.61	10.58
Bar	4.7	0.075	2.3	2.4	4.0	1.75	2.1	0.9	2.35	3.3	2.9	2.5
ΔBar			2.4	2.3	0.7	3.95	2.6	3.8	2.35	1.4	1.8	2.2
ΔBar/ΣΔBar = % of flow			10.2%	9.8%	3.0%	16.8%	11.1%	16.6%	10.0%	6.0%	7.7%	9.4%
l/min open			1.62	1.55	0.47	2.67	1.76	2.57	1.59	0.95	1.22	1.49
Area (m^2)			17.6	17.5	18.6	20	20.3	51.3	12.9	11.8	12.2	15.0
l/h/m^2			5.52	5.31	1.51	8.01	5.20	3.01	7.40	4.83	6.00	5.96

Figure 28: *Areas inclusive of the area surrounding inflow and backflow pipes.*

Pricing at Scale

Based on extrapolating our expenses in this project, eliminating any discounts, but also any overhead, we can reach the following estimate of pricing of a large-scale project, exclusive of feed-in and control system costs (rows in grey indicate options; assuming 165 ISK : 1 EUR):

	Unit price	**Units / ha**	**Total price**
Capital Expenses:			
25mm PEX (w/backflow)	*€1.00/m*	*18,000*	*€18,000*
25mm PEX (wo/backflow)	*€1.00/m*	*36,000*	*€36,000*
Structural frame	€0.50/m	18,000	€9,000
On-site assembly	€15/hr, 40s/m	18,000	€3,000
Placement	€80/200m^2	20	€1,600
Soil	*€20/m^3 , 0.25 m^3/m^2*	*10,000*	*€50,000*
Soil transport	*€75/30m, 0.25 m^3/m^2*	*10,000*	*€6,250*
Soil placement / forming	€80/h, 15min/50m^2	200	€4,000
Pumice	*€45/m^3 , 0.25 m^3/m^2*	*10,000*	*€112,500*
Pumice transport	*€200/30m, 0.25 m^3/m^2*	*10,000*	*€16,667*
Mulch	*€4/m^3, 0.25 m^3/m^2*	*10,000*	*€10,000*
Mulch transport	*€75/30m, 0.25 m^3/m^2*	*10,000*	*€6,250*
Insulation placement	€80/h, 15min/50m^2	200	€4,000

Operating Expenses:			
Water / year (30°)	*€0.09/m³, 16l/min/100m²*	*100 x 60x24x365*	*€75,686*
Water / year (35°)	*€0.13/m³, 8l/min/100m²*	*100 x 60x24x365*	*€54,662*
Pumice removal (6yr)	€80/h, 25min/50m²	*200 / 6*	*€1,111*
Pumice cleaning / replacement (6yr)	*€5/m³, 0.25 m³/m²*	*10,000 / 6*	*€2,083*
Mulch removal (2yr)	€80/h, 25min/50m²	*200 / 2*	*€3,333*
Mulch replacement (2yr)	*€4/m³, 0.25 m³/m²*	*10,000 / 2*	*€5,000*
Mulch transport (2yr)	*€75/30m, 0.25 m³/m²*	*10,000 / 2*	*€3,125*

From this, we have a VAT-inclusive fixed construction cost of €17,600 per hectare (€1.76/m²). To this one must add either €18,000/ha (€1.80/m²) for a no-backflow plumbing design or €36,000 (€3.60/m²) for one with backflow. If soil is required to be imported, this adds €56,250 per hectare (€5.63/m²). Insulation with pumice adds €129,167 per hectare (€12.92/m²), while insulation with with mulch instead adds €16,250 per hectare (€1.63/m²). For no-new-soil comparisons, with backflow, and assuming a 15-year amortization schedule at 7% interest, this equates to €19,713/yr/ha for pumice and €7534/yr/ha for mulch.

The ongoing costs for pumice adds €3,194/yr/ha, and for for mulch, €,/yr/ha. This yields a total for pumice of €22,907/yr/ha, and for mulch, €18,992/yr/ha. The costs are similar enough that factors such as insulation, resistance to pests, and potentially appearance are likely to dominate the decision.

Significantly greater than the maintenance and amortized capital costs is the cost of water. Higher-grade wastewater (35°), billed according to the rate established by Veitur, works out to €54,662/yr/ha. For 30° water, accounting for a higher flow rate to compensate for lower peak temperatures and lower energy content, works out to €75,686/yr/ha.

All together, the costs for such a setup appear to amount to approximately €75-100k/yr/ha, or €7.50-10.00/yr/m². If one only seeks to prevent soil freezing and extend the growing season, with only a moderate temperature rise, significantly lower flow rates could be used. This could allow for prices of under €30k/yr/ha (€3.00/yr/m²).

Conclusions

Comparison of Experiments

The results of the heat measurements are curious and not anticipated. The no-backflow experiments (#3, #8) have abnormally low flow rates per unit area, particularly #3 (mulch insulated). While one may partially explain this by backflow paths losing more heat due to them being shallower, experiment #2 (backflow deep between rows) is three times as high flow rate per unit area as experiment #3. Experiment #4 - with deeper burial - actually has the highest flow rate per unit area. And while all signs thusfar, including temperature gradient profiles, FLIR imagery, and even physical sensation showed the pumice as being more insulative than the mulch, the pumice experiments have a higher flow rate per unit unit area than most of the mulch experiments.

There's several aspects which could throw off these figures. Inflow and outflow paths en route to / from the experiments are parallel and may transfer heat to or from each other in unexpected ways. Some experiments (particularly the tree experiments, #9 and #10) have such long flow paths, under limited insulation, that the measurement may actually have more to do with how well they're insulated en route to the experiments than within the experiments themselves.

Lastly, air or debris may be creating false readings by hindering flow rates. Indeed, after conducting these measurements, then restoring all pathways to open, experiment #6 suffered from significantly reduced flow / heating in the following days (~ -4°). A surge of full-force water was plumbed through experiment #6 until heat rose significantly, then over the next several days, the experiments were rebalanced. The rebalancing points ended up similar to how they began, suggesting that whatever was interfering with experiment #6 was temporary.

Further measurements will be required in the future to help clear up these discrepancies.

Impacts To Growth

Measurements were taken on all beds - first from 25 August to 2 September, and then again from 12-27 September. The latter measurements took longer than the former due to worse weather and the aforementioned injury.

Pre-heating (red, blue) and post-heating trends (green, gold), both additive (+) and multiplicative (*), were plotted out relative to how well lit each individual plant was (1-9), and compared with controls (*Fig. 28*). Plants which straddled zones were counted as half in each zone.

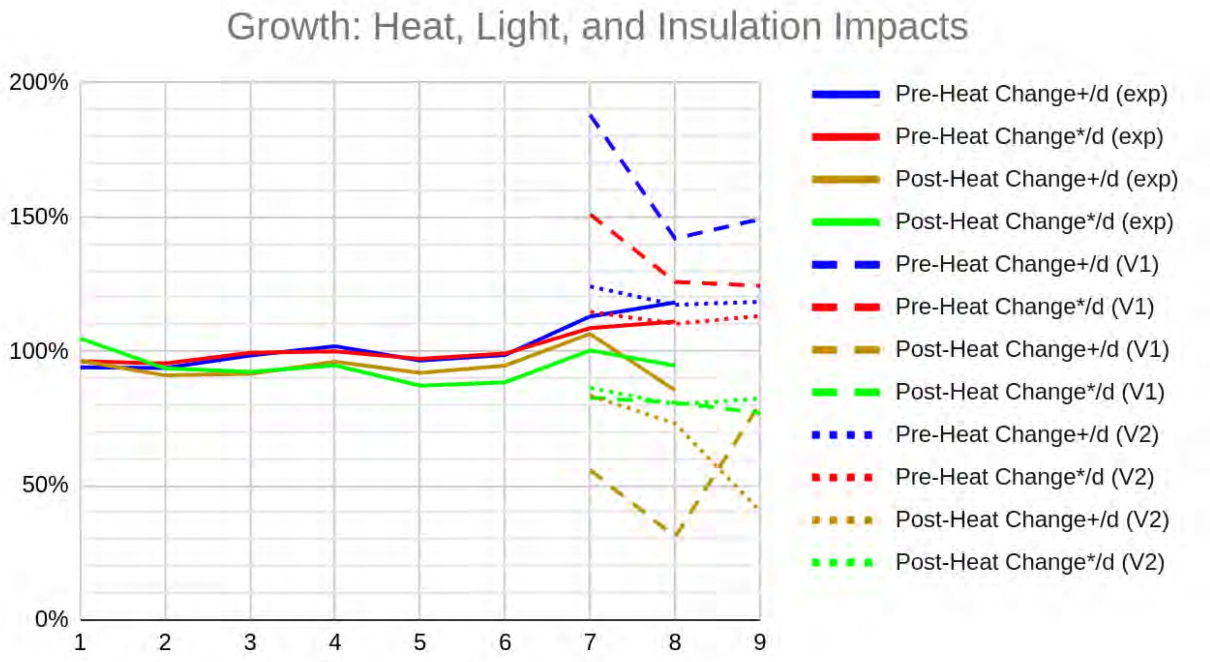


Figure 29: *Additive and multiplicative growth measurements (pre- and post-heating) relative to illumination (X-axis)*

As noted earlier, controls (V1 / uninsulated / dashed and V2 / insulated / dotted) were only located in locations that turned out to be well lit; only a small number even fit into zone 7 (adding noise to the dataset).

Preheating, it is clear that the uninsulated controls initially grew fastest, as would be expected from the sun warming the black soil. Insulated controls grew relatively similar to insulated experimental beds in their same lighting zone. After heating, however, the data diverges. The heated beds maintain similar rates to what they had during their early growth periods in the sunny, relatively warm weather of August, but the growth rates in the unheated beds fell off precipitously.

It is expected that the difference in growth rates will continue to expand as the weather continues to cool, through the point when the control beds freeze and all growth there ceases. How long we can maintain survival and growth in the heated beds as the weather increasingly worsens is at this point unclear.

Harvesting has been uneven due to the wide variety of plants and conditions, with some plants maturing early with small crops and other plants maturing late with larger crops. As the season is not yet complete, it is too early to draw harvest trends.

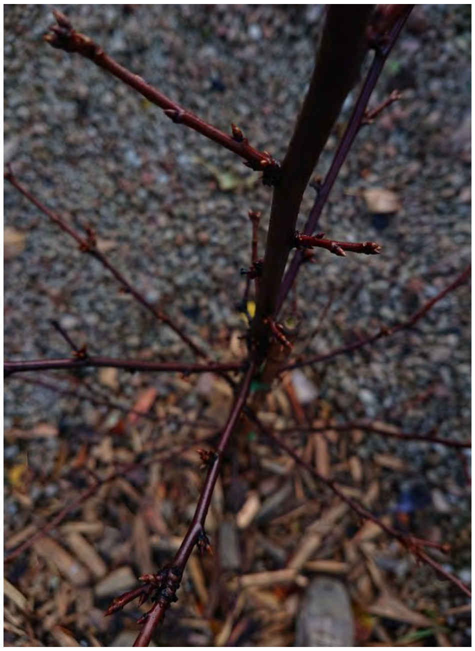


Figure 30: *Buds on Cherry 'Valentine' / 'Colt' (Experiment #9)*

Concerning the tree experiments, they too were measured, but showed no significant growth. This is presumed to be a consequence of them focusing their energies on establishing root systems and building up winter starch stores. The southwestern (experiment #9) cherry (the one on a Colt rootstock) had already begun changing colour before heat was applied, and by October was fully defoliated (but densely covered in healthy-appearing buds *Fig. 29*). Other trees are lagging a month behind. The impact of root heat to leaf senescence timing appears to be little to none. It is planned, as soon as all trees are fully defoliated, to reduce backflow temperatures on experiment #10 to 5° but leave experiment #9 at 23°, to compare the impacts on growth and flowering the subsequent spring.

Challenges

Most beds were planted from 25-29 July, in order #9-10, #v5, #1-6, #v1-v4, #7-8. #11 was not planted until 20 August, due to delays in acquiring compostable material, leading to the plants being stunted from rootbinding. The monstera and the larger banana plants were planted on 29 August - having had to wait until the heat was connected.

The late planting, due to delayed responses from the city of Reykjavík, and even later arrival of heat, led to an unsurprisingly poor result from the more heat-needy plants. This was amplified in the cucumbers which suffered from sunscald (which became infected with a fungus) and mites (*Fig. 30*). A treatment with neem was attempted but the plants - lacking meaningful root activity - were too far gone. The tomatoes suffered sunscald to a lesser degree. Both tomatoes and zucchini were listless, showing no growth and minimal fruit development. Only nine days after the start of soil heating and seven days after the planting of the monstera and large banana, a cold windstorm hit and killed the aboveground portions of all frost-sensitive plants. The soil-heated plants survived slightly better, but the winds combined with the surface insulation meant there was a relatively minimal boundary layer (*Fig. 31*). Bananas and zucchini attempted regrowth, particularly on the soil-heating side, but repeated evening frosts killed any new growth that emerged.

Figure 31: *Accumulated damage to cucumber*

Figure 32: *Insulated 25mm PEX from the source to the garden, being buried.*

A couple weeks after planting, aphids were noticed on all rose plants to varying degrees (*Fig. 32*). Winged aphids surrounded by young were on occasion spotted, indicating arrival by flying. While systemics were considered, they ultimately proved controllable by three applications of neem and hand-removal of visible pests over one week. Since it is unlikely that we discovered and removed every last aphid, it is presumed that predators provided lasting control. The roses also ceased all blooming activity during a cold spell with dim, freezing-nights. The return of the sun in early October led to a new, smaller wave of blooming from both heated and unheated beds; outer petals were frost damaged but the interiors remained intact.

Figure 33: *Aphids on rose 'Europeana'*

An ongoing challenge was with slugs in the wood-mulched beds. As a general rule, only brassicas were attacked, but some were attacked heavily (*Fig. 33*). Handpicking and two applications of iron phosphate were used to bring levels back under control, but some ongoing damage continues. Shady and edge-bordering beds were most impacted. Pumice beds suffered significantly less attack.

Figure 34: *Slug on broccoli 'Grön'*

Birds (primarily redwings) proved very interested in small fruits, including cherries, honeyberry, strawberries, blackcurrants, and to a lesser degree, tomatoes and plums. While harvests of most of these are not meaningful data at this point (reflecting more the plants previous cultivation before arrival in our garden), netting will be required next year.

Figure 35: *Grape 'Vroege van der Laan' in bloom*

For reasons unclear, the Vroege van der Laan grapes decided to bloom after the first frost (*Fig. 34*), and only a week before a harder frost defoliated all of the grape vines. The impact of this on their health next year is unknown.

A leg injury (bursitis) during measurement-taking limited how frequently I was able to check on the garden during the second week of September.

In late September, we suffered the theft of a celery plant.

Winds from storms became a major issue starting the second week in September, and ongoing. In addition to freezing the leaves of sensitive plants, brassicas and lettuce planted on the borders of pathways took wind damage, apparently from the stressing of roots, and two plants were outright uprooted. A tighter planting density and better wind shelter from the north would have reduced this impact.

Issues related to the hot water supply from Veitur were constant, including:

- Significant delays in responses to inquiries, delaying the arrival of hot water by weeks
- Charging for what’s currently wastewater
- Using the same energy content pricing (per joule) as for (more useful) hot water.
- Initially basing the lower end of the energy content on the ambient temperature (10°), even though water that cold is of no use to anyone.
- Basing the upper end of the energy content on a claimed 35° discharge temperature, even though the actual discharge temperature turned out to be only 29°.

- Taking over a month of requests to measure the actual discharge temperature from the source (*Fig. 35*) and correct the error.
- Charging the cost of a permanent connection, even though only a temporary connection was sought, and only the work needed for a temporary connection was conducted - again taking over a month to correct the error.

Figure 36: *Insulated 25mm PEX from the source to the garden, being buried.*

An additional, albeit much briefer problem occurred on our end, where flow rates were accidentally sized based on litres per second rather than litres per minute, leading to the ordering of 75mm hardware rather than 25mm. This was quickly corrected, thanks to assistance from Efla and Set.

While it was gratifying to work with numerous parties to collaborate in the project, it was at times frustrating how long it took to gain answers from the government, and future projects should consider the impact of delays from this cause to their cultivation plans. The combination of delays from the city and from Veitur combined led to a nearly three month delay between when funds were secured from the project and when heating began.

Figure 37: *Plant growth, from initial planting (left) to after the first frost (right)*

Discussion

- ***Is it possible to extend the outdoor cultivation period and have an impact on the size of the harvest and the diversity of species which can be cultivated by means of heating the soil with geothermal wastewater? If so, how much, and how impactful can it be?***

Setting up the experimental garden proved more challenging than anticipated, and delays limited the time and variety of data we could accumulate, but the data appears to support the hypothesis that heating with low-grade wastewater (29° from Veitur, 28° at the garden) can have a meaningful positive impact on plant growth rates (~20-180%, depending on the bed, lighting, and choice of metric). While the effects are limited - as anticipated, little benefit was realized in terms of extending the growing season of sensitive plants past the first frost - the ability to use a waste product to enhance crop growth warrants further investigation.

- ***What cultivation plan is optimal in terms of selected crop varieties and fruit trees?***

Certain details remain unclear. While infrared and probe measurements suggest highest heat loss through uninsulated soil, followed by mulch, with the least heat loss through pumice, attempts to estimate heat loss via flow rates / pressure drops yielded confusing or even contradictory data. At present we do not know how long we can extend the growing season into the winter, or how the various perennial plant species will survive the winter and grow the subsequent year. As the harvest is not complete, the total impact on yield is also unknown. The long-term picture is also unclear, as the wood mulch can be expected to rot over time, and thus its thermal conductivity should increase. Even pumice has the potential to break down into smaller grain sizes or accumulate organic material over time - albeit over longer timescales. Lastly, due to time and hardware limitations, we were not able to test an alternative technique for soil heating of using drip lines to leak warm water into the soil.

The approach of using insulation-filled trenches between rows proved not to be harmful to plant growth, while allowing us to use a greater average insulation depth over the soil; however, the optimal configuration requires further study. Plants grew well under both forms of insulation. In most measures, pumice appears to be a better, more convenient material, suitable for all environments; however, this has to be tempered with its higher cost, while wood mulch can be a waste product. In exposed areas, both materials might pose a risk of blowing away in the wind, although we did not experience this, and it’s possible that the plants fundamentally function as a windbreak, preventing this.

- ***What is the expected cost with setting up such a system, and over what timeperiod can it be repaid?***

If one seeks to have soil be warm (18-25° in the root zone), costs on the large scale appear to be approximately €75-100k/ha (€7.50-10/m²), including both ongoing costs and amortized capital costs. By contrast, if one simply wishes to prevent soil freezing, extend the growing season, and add a smaller temperature rise, this could potentially be accomplished for under €30k/ha (€3.00/m²).

- ***What are the potential benefits for farmers and gardeners in Iceland to implement such a system? What unexpected environmental impacts might there be from such a system?***

The presence of the heated garden proved not only to be attractive to wildlife by means of providing a potential food source (for better or worse), but additionally due to the heating itself. In particular, an unexpected consequence of the discharge trench is that local bird life (particularly redwings) appear to adore the warm bathing opportunity (Fig. 37).

Figure 38: *A redwing bathes in the warm outflow.*

While outdoor cultivation, even with soil heating, is not a substitute for cultivation of frost-sensitive plants inside enclosed, heated greenhouses, it appears to be significantly cheaper per unit area. In short, it provides a middle ground between costly greenhouse cultivation and low-yield short-season unheated outdoor cultivation – of particular interest for higher value-density outdoor crops (such as fruit). Further research, however, is required to see how well these benefits and costs can be realized in real-world settings.

Followup

The research garden now provides us with a baseline to continue experiments. This includes continuing through the harvest this year and utilizing a full growing season next year where we can apply what we’ve learned thus far - as well as providing the experience base from which new, more scalable garden projects could be developed. In particular, we would like to develop easily assembled modular plumbing frames which can be set down into the garden, buried with soil, optionally insulated, and plumbed together for rapid installation. This could enable utilization of this waste product both at home and commercial scales. Additional followup work would be required in terms of exploring tilling / planting / harvesting without damaging the plumbing system, as well as for how to restore insulative value (e.g. filtering out and cleaning the insulative material for reuse)

Gratitudes

I would like to offer my sincere thanks to Hjördís Sigurðardóttir for her relentless support in following up with third parties and getting this project pushed through, assisting with work in the garden, and in assisting in the drafting of this report.

A great debt of thanks goes to Jón Guðmundsson for his donation of plants and advice in their cultivation. Additional thanks go to Flóra nursery in Hveragerði for providing further plants at discounted rates.

Thanks go out to EFLA Consultanting Engineers - first to Heimir Hjartason for his initial assistance with the heating system design for the garden, and then to Unnar Víðisson for helping the resolve complications which arose.

I'd like to thank Stefán Gunnaugsson from Barr for making time for us to assist with excavator and transportation work on short notice, and for helping keep our budget down. I'd likewise like to thank our plumber, Reynir Baldursson, for likewise helping ensure that the water got connected as quickly as possible without excessive expense. Additionally, I wish to thank Arnar Pétursson for the construction of our valve cabinet.

Thanks go out to Veitur and the City of Reykjavík for their cooperation with this project.

Additional thanks go out to both Sorpa and Jarðaefnaiðnaður/JEI, for donating insulation materials to our project at no cost, and to Garðlist for supplying garden waste, again at only transportation-costs. I'd furthermore like to thank Gæðamold for offering our project discounted rates on our soil purchases.

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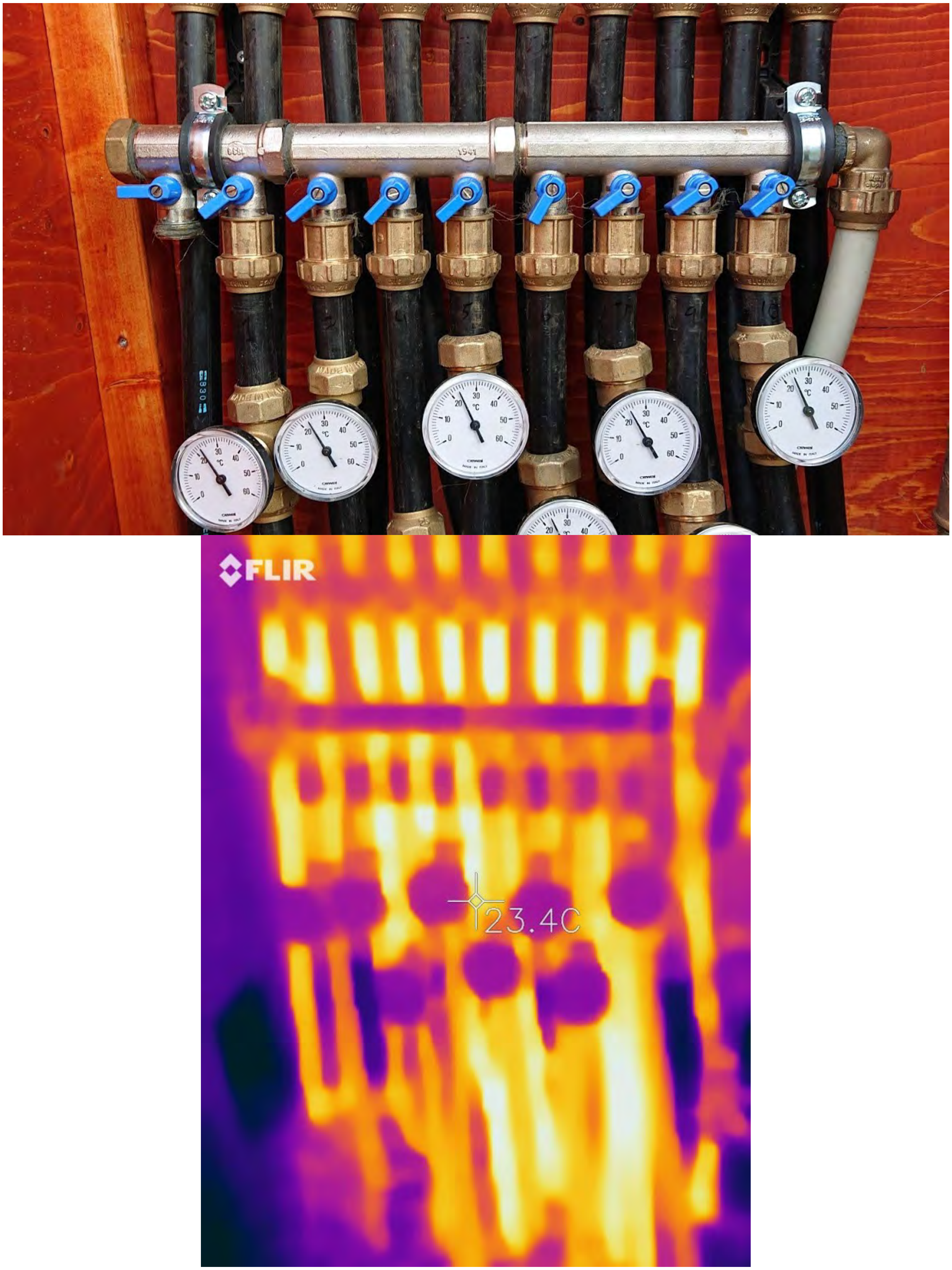
Appendix

Top to bottom: lettuce ‘Tantan’; cauliflower ‘Snowball’

Clockwise from top left: broccoli ‘Selster’; kale ‘Lerchenzungen’; red cabbage ‘’Bewaar; white cabbage ‘Primo’

Clockwise from top left: rose ‘Victor Borge’; lettuce ‘’Herkules’; miscellaneous lettuce and brassicas

Valve cabinet, visible (top) and infrared (bottom)



Infrared images, clockwise from top left: control #4 (unheated, uninsulated); outflow channel; experient #1-2 (mulch-insulated); experiment #5 (uninsulated; cool spots are plants)