

Intrarow soil thermal weeding: Research experiments report

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1. Table of contents

1. Table of contents	3
2. Summary	5
3. Introduction	6
3.1. Temperature and duration	7
3.2. Aggregate size	7
3.3. Heat type	7
3.4. Soil moisture content	7
3.4.1. Soil texture and SMC	8
4. Methods	9
4.1. Soil collection and preparation	9
4.1.1. Experiment 1 and 2	9
4.1.2. Experiment 3	9
4.2. Experimental apparatus	9
4.2.1. Steam and hot air supply	9
4.2.2. Retort and insulated drum	10
4.2.3. Treatment equipment	10
4.2.4. Measurement equipment and calibration	11
4.3. General methods	11
4.3.1. Soil Moisture Content	11
4.3.2. Soil heating and cooling	12
4.4. Individual experimental design	13
4.4.1. Experiment 1: temperature × aggregate size × heat type	13
4.4.2. Experiment 2: temperature × SMC	13
4.4.3. Experiment 3: soil texture × SMC	13
5. Results	14
5.1. Soil analysis	14
5.2. Experimental setup	15
5.3. Experimental results	15
5.3.1. Heating time for all experiments	15
5.3.2. Weedling emergence	16
5.3.3. Bulk density	17
5.3.4. Crush weight	17
5.3.5. Final weights	17
6. Discussion	18
6.1. Experimental setup	18
6.2. Heating time	18
6.2.1. Temperature	19
6.2.2. Aggregate size	19
6.2.3. Heat type	19
6.2.4. Soil moisture content and texture	20
6.3. Weedling emergence	22
6.3.1. Temperature	22
6.3.2. Soil Moisture Content	24
6.3.3. Heat type	25
6.3.4. Aggregate size	26



6.4. Bulk density	27
6.5. Crush weight	28
6.6. Final weights	28
6.7. Conclusions	28
7. Acknowledgements	30
8. References	31



2. Summary

- Intrarow soil thermal weeding (ISTW) is a technique for weed management / control based on killing the weed-seed bank in the intrarow (within the crop row) to weeds' maximum emergence depth.
- It is potentially unique among non-chemical weed management tools in that it is as, or even more, effective than herbicides and can therefore be used as a direct replacement.
- ISTW systems using steam have been developed and are in use in Scandinavia, but there remain a number of problems:
 - 100% weed kill is not being achieved;
 - The use of steam means the machinery is large, heavy and complex;
 - Large amounts of fossil fuel are used as the energy source.
- Previous reports in this series proposed hot air as the heat transfer medium, simplifying the machinery, and also potentially allowing recycling of the heat back from the soil. However, a number of issues needed further research:
 - If hot air was as 'effective' at soil heating and killing weed seeds;
 - The role of reduced treatment duration (due to heat recycling) on seed mortality;
 - The potential for higher temperatures to compensate for reduced treatment duration;
 - The effect of soil aggregate size;
 - The multiple influences of soil moisture on ISTW, including: energy requirements, seed mortality and the structure of silt and clay soils.
- Three complimentary experiments were conducted to address some of these issues:
 1. The effect of treatment temperature × aggregate size × heat type on seed mortality and heating time;
 2. The effect of treatment temperature × soil moisture content (SMC) on seed mortality and heating time;
 3. The effect of soil texture × SMC on soil structure and heating time.

Results

- **Heating times** are a proxy measurement for the underlying thermodynamics, so they are only a guide to the processes involved:
 - Larger aggregates needed less heating time to reach target temperatures than small aggregates indicating they are absorbing less heat, so will have lower seed mortality;
 - The longer heating time of air than steam was statistically significant but not physically large;
 - The effect of SMC was complex, with it increasing heating times but not in line with basic theory.
- **Weedling emergence** as a percentage of untreated controls:
 - Increasing temperature caused a large decrease in emerged weeds, but not as much as other experiments. SMC and the water content of steam were suggested as possible causes for this difference;
 - Larger aggregates produced significantly more weedlings, indicating they protect seeds from heat;
 - Increasing SMC caused a large reduction in weedlings.
- Simulating ISTW machinery operation showed that while the structure of sand texture soils are unaffected by treatment, silt and clay soils became exceptionally compact at the highest SMC, forming highly crush resistant clods.
- In conclusion, SMC and aggregate size the key soil parameters to understand to optimise ISTW. Thermal, or hydrothermal-time models may be better at predicting seed death than maximum temperatures. The moisture content of the heat source may be critical, although it may be substitutable by increased moisture in the target to be heated. Significant further research is required.



3. Introduction

Intrarow soil thermal weeding (ISTW) is a technique for weed management / control based on killing the weed-seed bank in the intrarow (within the crop row) to the maximum depth from which most weeds can successfully emerge from, immediately prior to sowing or planting annual or biennial crops, thereby preventing therophyte weeds from establishing in the intrarow for the entire duration of the crop, providing no viable weed-seed is introduced through activities such as cultivation or weed-seed rain. ISTW is considered unique among non-chemical weed management tools, in that it can match, and even exceed the abilities of herbicides, and has less 'downsides' in terms of non-target effects compared with herbicides, for example, ISTW is:

- broad spectrum, i.e. can control all therophyte weeds;
- can be used in any crop (although the economic return is unlikely to be viable for lower value crops);
- has a 'residual period' (i.e., it remains effective) as long as the crop's production cycle;
- has a nil withholding period;
- has no risk of releasing xenobiotic materials into the environment.

ISTW is therefore, unique among non-chemical weed management tools in potentially being a direct replacement for herbicides.

ISTW systems using steam was pioneered in the early 2000s in Denmark by Melander et al. (2002) and have continued to be researched (e.g., (Jørgensen *et al.*, 2004; Melander & Jørgensen, 2004; Kristensen *et al.*, 2005; Elsgaard *et al.*, 2010; Melander & Kristensen, 2011; Peruzzi *et al.*, 2012) and implemented by a small number of farmers / growers in Scandinavia.

However, the technique is considered to still be in the early stages of development and there continue to be issues that need to be resolved. The first two reports in this series on ISTW (Merfield, 2012a, 2012b), identified the key main / overarching issues of ISTW as being:

- Failing to achieve 100% weed control;
- The use of steam as the energy transfer medium, which increases the size and mechanical complexity of the machinery and creates safety issues;
- High energy use, which is currently from fossil fuels, with the multiple problems that entails, e.g., climate change.

The two reports also highlighted the specific issues that need further research. These are:

- To use hot air, rather than steam, as the heat transfer media, to simplify the size / weight and complexity of ISTW machinery, and to also allow heat recovery/recycling from treated soil to reduce the amount of energy used;
- Increasing the treatment temperature to improve seed kill;
- Studying the effect of reduced treatment duration on weed kill (as would happen with a heat recycling system);
- The effect of soil moisture content (SMC) on:
 - The energy required for treatment;
 - The effect on seed mortality;
 - The effect on soil structure of silt and clay soils.
- The effect of soil aggregate (particle) size on heating dynamics and seed mortality

Three complimentary experiments were therefore undertaken to address some of these issues:

4. The effect of treatment temperature × aggregate size × heat type on seed mortality and heating time;
5. The effect of treatment temperature × SMC on seed mortality and heating time;
6. The effect of soil texture × SMC on soil structure and heating time.



The purpose of each of the variables in the three experiments are discussed below.

3.1. Temperature and duration

As discussed in detail in (Merfield, 2012a) the effect of temperature on organisms can be divided into five 'zones'.

1. 'Lethal cold' temperatures below which death is very rapid, (e.g., below -40°C).
2. 'Semi-cold' temperatures below which negative effects start to occur and occur more rapidly with decreasing temperature (0 to -40°C).
3. 'Safe' temperatures at which there is no negative effects regardless of duration (0 to 40°C) i.e., the temperatures at which most life thrives.
4. 'Semi-hot' temperatures above which negative effects start to occur and occur more rapidly with increasing temperature (40-90°C).
5. 'Lethal hot' temperatures, above which death is very rapid, (90°C upwards).

Much of the previous work on steam based ISTW systems has focused on temperatures between ambient, e.g., 10-20°C and a maximum of 90°C (Melander *et al.*, 2002; Melander & Jørgensen, 2004). Treatment duration has generally be uncontrolled with the soil being left in situ until it has cooled to ambient.

In the heat recycling system proposed in (Merfield, 2012b) soils would be both rapidly heated and rapidly cooled which indicates that when temperatures are in seeds' semi-hot zone, the rapid cooling may have a negative effect on seed mortality.

These experiments therefore both increased the maximum temperature used to 100°C (the maximum possible temperature that can be achieved with steam at atmospheric pressure) and for expts. 1 and 2 the soil was immediately cooled after heating to simulate the effect of heat recovery.

3.2. Aggregate size

Aggregate size could have a number of effects because the heat transfer medium (steam or hot air) can only transfer heat to the outside of soil particles and aggregates, after which it has to move by conduction, which is much slower, often by orders of magnitude, than the forced convection of steam and hot air. Larger soil particle sizes (sand, silt and clay) and particularly aggregates of particles, could potentially absorb less heat (energy) especially in a heat recovery system of rapid heating and cooling, so the inside of the particles and aggregates will not get as hot as the outside. Aggregates could therefore provide a refugia for seeds from heating, reducing seed mortality. Expt. 1 therefore included four aggregate sizes as one of the factors to study this effect.

3.3. Heat type

While the production of steam compared with hot air in a field situation in agriculture is more difficult, there are a number of advantages of steam over air as a heat transfer media, for example energy density and no evaporative cooling of moist soils during heating. However, it is not possible to recover and recycle the heat from the soil with a steam heating system, and hot air is considered the most only practical means to achieve this. Therefore, initial comparisons of hot air and steam heating of soil, using the same energy throughput, needs to be undertaken to see if there are significant differences between them, especially in terms of seed mortality. Expt. 1 therefore included heat type as one of the three factors.

3.4. Soil moisture content

Soil moisture content has a number of conflicting effects on ISTW:



- Increasing SMC increases the mass (amount) of material to be heated so it should require more energy to achieve target temperatures;
- Increasing SMC increases the rate of heat flow within soil, which could increase seed mortality;
- When soils are being tilled (mixed) SMC can have a large influence on the integrity of soil structure, especially for silt and clay soil textures, i.e., structure can be damaged at higher SMCs;
- Plant seeds, including weed seeds are known to be more susceptible to heat when they are moist than dry, so weed seed mortality should be higher at higher SMCs.

Expts. 2 and 3 included SMC as one of the factors to study the effect of soil moisture on heating time, seed mortality and its effect on soil structure of the three main soil textures, i.e., sand, silt and clay. The practical issues relating to the interaction of soil texture and SMC are discussed below.

3.4.1. Soil texture and SMC

Intrarow soil thermal weeding (ISTW) research and use in real-world farming has been conducted in Denmark and Sweden on predominantly sandy soils. Generally, these soils have little structure, and while they can have high bulk densities, they are comparatively resistant to forming compact aggregates i.e., soil clods. However, silt and clay soil textures, that are often sort after by farmers and growers around the world due to their high inherent fertility (Brady & Weil, 2008), can form dense clods when compacted, especially when the soils are in a plastic state, i.e., at higher soil moisture contents.

In the first report in this series, (Merfield, 2012a) it was claimed that different soil textures, e.g., sand, silt, and clays, would respond differently to ISTW in terms of the effects on soil structure and that soil moisture content (SMC) would interact with texture, e.g., sand soils have a similar response to ISTW treatment regardless of SMC while silts and clays may respond quite differently depending on SMC. The key concern is that the ISTW process of steam heating while mechanically mixing soils, especially at higher moisture contents, could result in silt and clay soils becoming so severely compacted that there would be significant negative impacts on crop growth (the effects of compaction on plant growth being well known, (Davies *et al.*, 2001; Brady & Weil, 2008)).

Whole-soil steaming, which is the standard means of steaming soil, inevitably leaves the soil with elevated SMC, often at field capacity or even beyond, due to the large amount of water that condenses over the treatment period (Gay *et al.*, 2010a, 2010b). If steam based ISTW also significantly elevates SMC, which in turn results in significant compaction, then it may be impossible to use it on such soils.

ISTW treatment in this respect is simply a subset of normal soil tillage and traffic processes, which are well understood in terms of their effect on soil structure and the subsequent effect on plant growth. However, no research has been found on the effect of both heating and tilling soil followed by moderate compaction, so it was considered worthwhile to undertake an experiment that directly addressed this issue by simulating existing ISTW machinery e.g., (Kristensen *et al.*, 2005), and compare its effect on the structure of three contrasting soil textures, a sand, silt and clay, across a range of SMC from dry to field capacity.

In addition, the counter-flow, hot air ISTW concept described in (Merfield, 2012b) would require a good gas seal at the rear of the treatment tunnels to ensure that the cold air being forced into the tunnel at that point, does not simply blow back out of the rear of the tunnel, rather than travelling up the tunnel, against the soil flow. One of the options to achieve a sufficiently good gas seal against both the sides and top of the tunnel, and more critically, against the soil, would be a small roller. Such a roller would have to exert sufficient downwards pressure to create an effective seal against the soil, which will have a compacting effect. The design of expt.3 aims to simulate the mixing of the soil by the multiple tillage rotors of the Danish ISTW machine (Kristensen *et al.*, 2005) and the roller at the rear of the tunnel of the counter-flow hot air ISTW machine proposed in (Merfield, 2012b).



4. Methods

4.1. Soil collection and preparation

4.1.1. Experiment 1 and 2

Stone-free soil was collected from the Biological Husbandry Unit, at Lincoln University, Canterbury New Zealand, from the Crowder Tunnel 1 (43°38'59.68" S 172°27'21.63" E) for expt. 1 and Crowder Tunnel 2 (43°39'00.57" S 172°27'21.78" E) for expt. 2. (the coordinates are the exact sampling points to within five meters). The soil is described as a Templeton silty loam (<http://smap.landcareresearch.co.nz>). The soils in the tunnels have received substantial amounts of organic matter, mostly as compost, in the previous decades, and therefore had generally good structure. Soil analysis results for tunnel 1 are presented in the results.

Both sites were considered to have a very substantial natural seedbank, which was essential for expt. 1 as it was not possible to add seeds to the soil (artificial seedbank) as these would reside between, not within, soil aggregates so could not provide any data on the effect of soil aggregates on seed mortality.

Soil for expt. 1 was placed on a plastic sheet on the floor of an enclosed workshop, about 6 cm deep for three weeks, and stirred weekly. It was then sieved to produce four sizes of aggregates: 1.0-2.8 mm, 2.8-5.6 mm, 5.6-8.0 mm and 8.0-19 mm. Aggregates larger than 19 mm and the soil fraction smaller than 1.0 mm were discarded.

Soil for expt. 2 was pushed through a 6.35 mm sieve after collection, i.e., unlike expt. 1, all the collected soil was retained, regardless of aggregate or particle size. The soil was then placed approx. 4 cm deep in large plastic trays in a glasshouse to air dry for three weeks.

Soils for both experiments were then stored in 20 L air tight containers until the start of the experiments.

4.1.2. Experiment 3

Three stone-free soils, a sand, silt and clay that were considered to be good examples of their texture classes were collected from the Canterbury region of New Zealand. The sand was collected from Spencer Park, 43°25'48.16" S 172°42'31.90" E, from under deciduous trees, it is described as Kairaki sandy loam (<http://smap.landcareresearch.co.nz>) and originated as beach sand / sand dunes. The silt was collected from the Biological Husbandry Unit at Lincoln University, 43°39'00.92" S 172°27'30.48" E, it is classed as a Templeton silty loam and has been under mixed cropping and pasture, being under pasture for the two years prior to collection. It was considered to have good structure. The clay was collected from the farm of Bruce Gill, Doyleston, 43°45'15.23" S 172°19'59.32" E, it is classed as Ayreburn clay, it was under long term pasture used for cattle grazing and was considered to have poor structure due to compaction from the livestock.

The soils were pushed through 6.35 mm sieve after collection, to standardize the maximum aggregate size and simulate the effects of tillage, i.e., as in expt.2 all the collected soil was used in the experiment. The soils were then placed approx. 4 cm deep in large plastic trays in a glasshouse to air dry for three weeks. They were then placed in 20 L air tight containers for storage until the start of the experiment.

4.2. Experimental apparatus

4.2.1. Steam and hot air supply

Steam was generated using a 60 L capacity, insulated, domestic electric hot water cylinder, with a 3 kw element. This was connected to the retort (see below) via a 300 mm long insulated steel pipe.



Hot air was generated using two, Bosch PHG 630 DCE, 240 V 2000 W, hot air guns. These were connected to the retort (below) via a 'Y' shaped adaptor made of 32 mm internal diameter metal pipe, with arms approx. 50 mm long, i.e., as short as possible.

4.2.2. Retort and insulated drum

A heating retort was constructed from steel, consisting of a pipe 155 mm internal diameter (ID) 300 mm high, with the bottom end blanked off. Halfway up the pipe was a 5 mm thick baffle plate with one hundred 5 mm dia. holes, equidistantly spaced. An 'inlet pipe', 32 mm ID, 100 mm long was connected to the lower part of the retort (i.e., below the baffle plate) 30 mm from the bottom blanking plate which was connected to the hot water cylinder or hot air guns. A 'drain pipe' 10 mm ID, 1,000 mm long was connected to the opposite side of the retort from the inlet pipe at the bottom: and a two meter long 10 mm ID hose was connected to the end of the drain pipe. The drain pipe was to allow any water condensing from the steam to be vented from the retort, i.e., to prevent it building up. It also allowed any accumulated soil dust to be flushed from the retort with water. The overall length and diameter of the drain pipe and hose provided sufficient resistance that all of the hot gasses exited through the top of the retort and the soil being treated, not through the drain pipe, which only vented liquid water when steam was being used. The design aim of the retort was to ensure an even and steady flow of hot gasses through the soil being treated.

The retort was then placed inside a steel drum, 380 mm dia. and 400 mm tall, with the open end of the main pipe facing upwards, with the retorts inlet and drain pipes protruding through the drum walls. The space between the drum and retort was then filled with vermiculite. There was 50 mm of vermiculite under the retort, and the vermiculite stopped 40 mm below the top of the retort. The design aim of the drum and vermiculite was to insulate the retort so to minimise heat / energy loss, from the retort and thus ensure the maximum amount of the hot gasses generated would pass through the soil.

Prior to use with each heat type, the system was run for 20 min, to ensure that all the apparatus was at a constant temperature, i.e., to fully heat up. This was verified by a constant temperature reading from the infrared thermometer (see below).

4.2.3. Treatment equipment

A treatment basket was constructed from stainless steel mesh (0.294 mm wire, 0.55 mm aperture), in the form of a cylinder closed at one end, that fitted 'snugly' inside the retort, i.e., the basket could be removed and inserted with only slight force, but the basket was in full contact with the inside of the retort, to ensure that all gasses flowing through the retort had to pass through the bottom of the basket and therefore the soil in the basket and not between the basket and retort.

A manual 'stirrer' for mixing / stirring soil in the basket was constructed of two 60 mm long, 25 mm wide and 3 mm thick steel flat bars, welded at 90° to each other by their 25 mm edge to form a propeller shape. This was then welded at the weld point of the two blades to a 10 mm round bar 400 mm long. The stirrer was required to ensure even soil heating. The stirrer was rotated in the basket so that the soil was lifted upwards by the blades.

For expts. 1 and 2, a soil cooling system was made from a PVC pipe 160 mm ID, 280 mm long, with one end blanked off, an internal collar half way down the length restricted the ID to 120 mm, and a 30 mm ID hole was cut through the side of the pipe 20 mm from the blanked off end. The hose from a domestic vacuum cleaner (Nilfisk Action Plus CLE) was inserted into the 30 mm hole, so it could suck or blow air out or into the pipe. With the pipe standing on its based, the treatment basket containing the soil was then placed into the pipe to rest on the internal collar, and air was blown or sucked through the soil by the vacuum cleaner on its lowest power setting. In expt. 1 the air was blown through the sample and sucked through in expt. 2. Sucking the air through the soil prevented very fine soil particles being blown out of the basket, which occurred when air was blown through the soil and it also cooled the sample



quicker and to a lower temperature as the air being blown from the vacuum had a temperature of approx. 30°C.

For expts. 1 and 2, for weed seed germination, each soil sample was placed in a plastic container, 165 × 165 × 85 mm (width, length, depth) with eight 5 mm holes drilled around the bottom edge at the corners and middle of the sides. 25 mm of medium grade vermiculite was evenly placed in the bottom of the container, and two layers of muslin cloth were placed on top of the vermiculite, onto which the soil samples were spread. The containers were placed in large plastic trays 70 mm deep, holding 20 containers each, in block order, and bottom watered so to keep the soil moist but not wet. The trays were placed in a heated glasshouse with a recorded minimum temperature of 10°C, maximum 28°C and average 19°C.

For expt. 3, to simulate the mechanical mixing used in the 'Danish design' ISTW machine, (Kristensen *et al.*, 2005), a PVC 'mixing pipe' was used, 100 mm ID, 250 mm tall with one end capped. To mix the soil a helical type paint mixer 85 mm in diameter with the two blades reaching 120 mm up the shaft, was used. The mixer was rotated by an electric mains drill, to ensure consistent rotation speed, with the drill rotating anticlockwise, at approx. 100 rpm for five seconds. The drill was run anticlockwise so the paint mixer lifted the soil upwards rather than forcing it downwards, creating a more gentle mixing action. The mixer was moved up and down five times during the process to ensure even mixing.

For expt. 3, soil compression pipes were made from PVC pipe 75 mm ID and 120 mm long. They were smeared with Vaseline on the inside to minimise soil adhesion to the pipe. To compress the soil, a plunger was used. made of a plastic container filled with cement, that fitted snugly into the compression pipes.

4.2.4. Measurement equipment and calibration

Due to the continual mixing of the soil in the retort with the steel mixer and the poor contact between a probe and the larger aggregate sizes of expt. 1, it was impossible to use a standard probe / thermocouple type thermometer to measure the temperature of the soil during treatment, so a 'non-contact' infrared thermometer was used (Mastech MS6530 infrared thermometer). This was mounted on a camera tripod with the thermometer placed approx. 60 cm from the surface of the soil being heated in the retort. Due to infrared emissivity varying among materials, the infrared thermometer was calibrated using a probe thermometer (RS 206-3722 digital thermometer using an RS 342-8899 type 'K' general purpose probe / thermocouple) by heating 500 g of dry silt soil to 140°C, then placing it in an aluminium tray, placing the digital thermometer probe on the soil surface and simultaneously taking the temperature of the soil next to the probe with the infrared thermometer placed 60 cm from the soil surface. Temperature readings were taken from the infrared thermometer for every 10°C between 130 and 40°C as measured by the probe thermometer. This was repeated three times (three replicates). The mean of three sets of readings provided the emissivity calibration.

The electrical power consumed by the hot water cylinder and hot air guns was measured using an Owl® CM119 OWL domestic electricity monitor.

4.3. General methods

4.3.1. Soil Moisture Content

To achieve a range of SMC for expts. 2 and 3, the soils were initially air dried (described above), and then sub-samples were taken from five different depths within the storage containers, then combined to give a minimum of 50 g of soil, then the SMC was determined using the gravimetric method (Brady & Weil, 2008) with percentage SMC calculated as $((\text{soil wet weight} - \text{soil dry weight}) / \text{soil dry weight}) \times 100$. The



starting SMC of the four aggregate sizes in expt. 1 was separately determined for each aggregate size, again using five sub-samples.

For expts. 1 and 2, the amount of water that needed to be added to bring each soil up to the target SMCs was calculated (Table 1) and then confirmed, using the gravimetric method, during pre-experimental testing.

Table 1. The amount of water added (g) to each 400 g of soil to achieve the four target SMC (Table 2) for each soil texture in expt. 1 and the single soil texture (silt) used in expt. 2.

	Sand	Silt	Clay	Expt. 2
A	17.2	10.5	1.5	0
B	37	30	61	27
C	77	70	121	67
D	117	110	181	107

The soils for expts. 1 and 2 were divided into 400 g samples and placed in 20 × 30 cm re-sealable plastic bags. The water was then added to the bags and then briefly mixed by tumbling the soil within the bag. For expt.1 the bags were then left for 24 hrs for the water and soil to equilibrate. For expt. 2 the bags were left for 48 hours for the water and soil to equilibrate and for the weed seeds to become fully imbibed but before they started to emerge. The bags for expt. 2 were tumbled after 24 hours to promote even mixing, and for both experiments the bags were again tumbled immediately prior to treatment, including breaking up any lumps that had formed.

In expt. 3 Different SMC were used for the different soil textures as they have different moisture holding capacities and the objective was to have the highest SMC close to field capacity for each soil texture. Field capacity for each soil texture was empirically determined in pre-experimental testing by adding a range of volumes of water to each soil type and determining the maximum volume of water the soil could fully retain, i.e., at higher water volumes the soil failed to absorb all the water and some drained out. This amount was then slightly reduced to take into account the extra water absorbed by the soil during steam heating, so that the soils at SMC 'D' were at field capacity post treatment.

4.3.2. Soil heating and cooling

The soils were heated by placing them in the stainless steel mesh treatment basket, which was then placed in the retort, and slowly mixed, at about 0.5 to 1 revolutions per second, using the manual stirrer. The basket was removed when the average temperature readout on the infrared thermometer showed the target temperature had been reached. A manual stopwatch was used to record the duration of heating.

Considerable care was taken to ensure that as little soil as possible was left in the treatment basket and the mixing pipe (used in expt. 3), especially for the clay and silt textures at higher SMCs as these adhered strongly to the equipment. A mixture of brushes, scrapers and compressed air were required to thoroughly remove the soil.

To cool the samples the treatment basket with the soil was placed into the cooling system. Samples were left in the system while the following sample was prepared for heating, which took approx. two minutes. This was ample time for the soils to cool to ambient temperatures (the temperature of the air from the vacuum when blowing ~30°C, and air temperature when sucking, approx. 20-25°C), which generally took less than 10 sec as determined during pre-experimental testing.



4.4. Individual experimental design

4.4.1. Experiment 1: temperature × aggregate size × heat type

The experiment had three factors:

1. Treatment temperatures of: 60, 70, 80, 90 and 100°C and an untreated control at ambient ~20°C;
2. Aggregate size of: 1.0-2.8 mm, 2.8-5.6 mm, 5.6-8.0 mm and 8.0-19 mm;
3. Heat type: hot air and steam.

There were three replicates giving a total of 132 samples. Replicates were used as blocks for heating and arranging germination containers the glasshouse. Application of the different heat types to the soils within blocks could not be randomised due to the time taken to change from steam to hot air. Within blocks the order of steam or hot air was randomly chosen. All other aspects of the experiment were randomised.

Measurements were: the time taken to reach the target temperature and the number of emerged weed seedlings. Statistical analysis was by ANOVA.

Soil sample size was 270 g which were stored in resealable plastic bags prior to treatment. Soil samples were heated as described above and the time taken to reach the target temperature recorded.

Immediately after removal from the heating retort, they were placed in the cooling system, with the air blown through the sample. The soil was then returned to the plastic bag, and the following day, placed in the seed germination containers (described above) and put in the glasshouse for 20 days. Emerged weed seedlings were then counted with dicotyledons and monocotyledons recorded separately. As there were very few monocotyledons (14 in total) the two datasets were combined. The number of seedlings were then converted to a percentage of the untreated control of the same aggregate size within each replicate.

4.4.2. Experiment 2: temperature × SMC

The experiment had two factors:

1. Treatment temperatures of: 60, 70, 80, 90 and 100°C and an untreated control at ambient ~20°C;
2. Soil moisture content: 3.3%, 10%, 20% and 30%.

There were four replicates giving a total of 96 samples. Replicates were used as blocks for heating and arranging germination containers the glasshouse. All other aspects of the experiment were randomised.

Measurements were: the time taken to reach the target temperature, the number of emerged weed seedlings. Statistical analysis was by ANOVA.

Soil sample size was 400 g which were stored in resealable plastic bags prior to treatment. SMC was adjusted as described above. Soil samples were heated with steam as described above and the time taken to reach the target temperature recorded. Immediately after removal from the heating retort, they were placed in the cooling system, with the air sucked through the sample. The soil was then returned to the plastic bag and on the same day placed in the seed germination containers, described above, and put in the glasshouse for 22 days. Emerged weed seedlings were then counted with dicotyledons and monocotyledons recorded separately. As there were very few monocotyledons (15 in total) so the two datasets were combined. The number of seedlings were then converted to a percentage of the untreated control at the same SMC within each replicate.

4.4.3. Experiment 3: soil texture × SMC

The experiment had two factors:

1. Soil texture: three textures, sand, silt and clay;



2. Soil moisture content: four levels (Table 2).

Table 2. The four target soil moisture contents of the three soil textures.

	Sand	Silt	Clay
A	5%	5%	5%
B	10%	10%	20%
C	20%	20%	35%
D	30%	30%	50%

In addition there was an 'untreated' control for each soil texture that was not heated or mixed but was compressed in the compression pipes by the 1 kg plunger only i.e., not the additional 19 kg weight. There were four replicates giving a total of 60 samples including the 'controls'. Replicates were used as blocks for soil heating and mixing. All other aspects of the experiment were randomised.

Measurements were: the time taken to reach 90°C, the 'bulk density' of the treated soil cylinders, final soil weight, and the weight required to crush the dried soil cylinders. Results were analysed by ANOVA.

The prepared soils were heated with steam, as described above, to 90°C. Then, immediately post heating, while the soil was still hot, it was transferred from the basket to the mixing pipe. It was then mixed with the paint mixer. The soil was then transferred to a compression pipe, which was itself placed in a plastic tray. The plunger was then placed into the top of the pipe and a 19 kg weight placed on top of the plunger for five seconds. The 19 kg weight combined with the 1 kg weight of the plunger, gives a total weight of 20 kg. As the pipe was 75 mm in diameter this gives a force of 0.45 kg·cm² of soil surface. This weight was selected as the compressive factor that might be imposed by ISTW machinery, being greater than exerted by a human e.g., 0.12 kg·cm² (own calculation) but less than a tractor at 1.0 kg·cm² (Davies *et al.*, 2001).

After all the samples were treated, the bulk density, on a dry weight basis, was calculated by measuring the height of soil in the pipe to determine its volume, then calculating the oven dry weight of the soil from its initial 400 g and its SMC (for each texture) and dividing the dry weight by the volume.

The trays containing the compression pipes with the soil inside them, were then placed in a drying cabinet at 25°C for two weeks. After drying, the weight of the soil from each pipe was recorded. The soils were then removed from the pipes using the plunger to eject them as an intact cylinder if required. They were then subjected to a crush test. Those soils where the individual particles or aggregates had not adhered to each other, i.e., they 'fell apart' on removal from the pipe were considered to have zero compressive strength. Those soils where the particles or aggregates did adhere to each other were crushed either: (1) using a handheld penetrometer by placing the soil cylinder on a firm flat surface, placing a 75 mm diameter circle of 12 mm plywood on top of the soil cylinder and placing the penetrometer shaft in the centre of the plywood circle; or, (2) they were crushed using an industrial compression testing machine. The penetrometer was used for soil samples with a crushing weight of < 10 kg and the industrial machine for samples that required > 10 kg to crush them. The crush weight was taken as the maximum weight that was required for the soil cylinder to initially fail.

5. Results

5.1. Soil analysis

The soil analysis for the Crowder Tunnel one (for expt. 1) was pH, 7.2, Olsen phosphorus 128 ml·L, potassium 1.61 me·100g, Calcium 21.7 me·100g, organic matter 8.4%. The analysis for the soil from Crowder Tunnel 2, used in expt. 2 is similar. No soil analysis was undertaken for expt. 3.



5.2. Experimental setup

The power used by the hot water cylinder was a constant 2.8 kw. The hot air guns were set at 350°C and used 2.6 kw, averaged over 15 mins.

The emissivity calibration for the infrared thermometer is listed in Table 3.

Table 3. Emissivity calibration for the infrared thermometer.

Probe temperature °C	130	120	110	100	90	80	70	60	50	40
Mean infrared thermometer temperature, n=3	127	110	98	89	80	71	63	55	47	38
SD	5.5	4.1	4.1	4.1	4.2	3.5	2.0	1.6	1.2	0.4

The SMC of the soils after air drying, i.e., before additional water was added were: For expt. 1, the SMC of the four aggregate sizes were 1.0-2.8 mm 3.0%, 2.8-5.6 mm 3.2%, 5.6-8.0 mm 3.2% and 8.0-19 mm 3.6%. For expt. 2 the SMC was 3.34%. For expt. 3, the SMC of the three soil textures was sand 0.71%, silt 2.38% and clay 4.61%.

5.3. Experimental results

5.3.1. Heating time for all experiments

For expt. 1 (temperature × aggregate size × heat type), the heating time for the three way interaction was not significant $p=0.093$. For the two way interactions it was not significant for aggregate size × temperature $p=0.241$ or heat type × temperature $p=0.086$ but it was significant for aggregate size × heat type $p=0.006$. The individual factors were all significant: aggregate size and temperature $p<0.001$ and heat type $p=0.021$. Significant results are presented in Table 4 and Table 5.

Table 4. The effect of the interaction of aggregate size × heat type on heating time (seconds), $LSD_{0.05}$ 3.01, and the individual factors of aggregate size (mean column) $LSD_{0.05}$ 2.13, and heat type (mean row) $LSD_{0.05}$ 1.50.

Aggregate size	Heat type		Mean
	Air	Steam	
1.0-2.8 mm	19.7	16.1	17.9
2.8-5.6 mm	17.1	13.0	15.0
5.6-8.0 mm	13.9	11.6	12.8
8.0-19.0 mm	10.1	13.0	11.6
Mean	15.2	13.4	

Table 5. The effect of temperature on heating time (seconds), $LSD_{0.05}$ 2.38.

	Temperature °C				
	60	70	80	90	100
Heating time (s)	8.4	10	13.2	16.4	23.6

For expt. 2 (temperature × SMC), the interaction of SMC × temperature was significant $p>0.001$ as were the individual factors: SMC $p=0.034$ and temperature $p>0.001$.



Table 6. The effect of the interaction of SMC x temperature on heating time (seconds), $LSD_{0.05}$ 14.45, and the individual factors of SMC (mean column) $LSD_{0.05}$ 6.46, and heat type (mean row) $LSD_{0.05}$ 7.23.

SMC	Temperature °C					Mean
	60	70	80	90	100	
A	16.2	22.2	29.0	39.5	83.8	38.1
B	21.8	30.8	36.0	43.2	80.0	42.4
C	22.2	29.2	35.0	38.8	47.5	34.5
D	23.3	27.3	31.5	38.8	46.5	33.5
Mean	20.9	27.4	32.9	40.1	64.4	

For expt. 3 (soil texture x SMC), the heating time for the soils was statistically significant for the interaction of SMC and texture and for the individual treatments, $p < 0.001$, (Table 7).

Table 7. The effect of the interaction of soil texture and soil moisture content on heating time (seconds) $LSD_{0.05}$ 8.35, and the individual factors of SMC (mean column) $LSD_{0.05}$ 4.82 and texture (mean row) $LSD_{0.05}$ 4.18.

SMC	Texture			Mean
	Clay	Sand	Silt	
A	35.5	39.8	40.8	38.7
B	50.0	39.5	43.3	44.3
C	52.3	44.8	48.5	48.5
D	108.0	105.0	46.5	86.5
Mean	61.5	57.3	44.8	

5.3.2. Weedling emergence

For expt. 1, the percentage of emerged weedlings compared with the controls for the three way interaction was not significant $p = 0.950$ or the two way interactions: aggregate size x temperature $p = 0.987$, heat type x temperature $p = 0.899$ and aggregate size x heat type $p = 0.155$. The individual factors were all significant at $p < 0.001$, Table 8, Table 9 and Table 10.

Table 8. The effect of temperature on emerged weedlings as percentage of the controls, $LSD_{0.05}$ 8.9.

	Temperature °C				
	60	70	80	90	100
% emerged weedlings	48	43	37	32	29

Table 9. The effect of aggregate size on emerged weedlings as percentage of the controls, $LSD_{0.05}$ 8.0.

Aggregate size	% emerged weedlings
1.0-2.8 mm	29
2.8-5.6 mm	35
5.6-8.0 mm	41
8.0-19.0 mm	46

Table 10. The effect of heat type on emerged weedlings as percentage of the controls, $LSD_{0.05}$ 5.6.

	Heat type	
	Air	Steam
% emerged weedlings	63	12

For expt. 2, the percentage of emerged weedlings compared with the controls for the interaction of SMC x temperature and the individual factors were all significant $p > 0.001$.



Table 11. The effect of the interaction of SMC x temperature on emerged weedlings as percentage of the controls, $LSD_{0.05}$ 6.02, and the individual factors of SMC (mean column) $LSD_{0.05}$ 2.69, and heat type (mean row) $LSD_{0.05}$ 3.01.

SMC	Temperature °C					Mean
	60	70	80	90	100	
A	50.0	44.5	17.3	11.0	4.8	25.5
B	19.3	11.0	3.8	0.8	0.0	7.0
C	15.0	7.8	4.0	1.3	0.5	5.7
D	10.5	6.5	3.8	1.3	0.5	4.5
Mean	23.7	17.4	7.2	3.6	1.4	

5.3.3. Bulk density

In expt. 3, the effect on bulk density ($\text{g}\cdot\text{cm}^{-3}$) was significant for the interaction of SMC x soil texture $p=0.003$ and the individual factors $p>0.001$ (Table 12).

Table 12. The effect of the interaction of soil texture x SMC on bulk density ($\text{g}\cdot\text{cm}^{-3}$) after heating, mixing and compressing the soils plus an untreated control (U) $LSD_{0.05}$ 0.022, and the individual factors of texture (mean row) $LSD_{0.05}$ 0.062 and SMC (mean column) $LSD_{0.05}$ 0.080.

SMC	Texture			Mean
	Clay	Sand	Silt	
U	0.89	1.39	1.03	1.10
A	1.08	1.21	1.21	1.17
B	1.08	1.22	1.17	1.15
C	0.98	1.38	1.28	1.22
D	1.12	1.40	1.33	1.28
Mean	1.03	1.32	1.20	

5.3.4. Crush weight

The effect on crushing weight (kg) was significant $p<0.001$ for the interaction and individual treatments (Table 13). The means for the individual factor are not shown as these are considered to be of no practical information.

Table 13. The amount of weight (kg) required to crush the dried soil cylinders, $LSD_{0.05}$ is 73.38.

SMC	Texture		
	Clay	Sand	Silt
U	0.0	0.0	0.0
A	0.0	0.0	0.0
B	3.9	0.0	0.0
C	114.7	3.7	125.8
D	1,286.3	2.4	795.4

5.3.5. Final weights

The final weights of the soil cylinders after drying is presented in Table 14. These were not statistically analysed as they are not experimental results but are for cross-checking the methodology.



Table 14. The final weight (g) of the soil cylinders after drying.

SMC	Texture		
	Clay	Sand	Silt
U	398	396	398
A	392	394	387
B	394	392	392
C	390	392	395
D	383	390	387

6. Discussion

6.1. Experimental setup

The heating apparatus design is considered to be basic but sufficient for the purposes of this research, because it is primarily studying biological outcomes, which have inherent large natural variation, e.g., seedling emergence, rather than the physical parameters, which have smaller variation.

It important to note that the open retort heating system is quite different to enclosed heat transfer systems, such as fluidised bed heat exchanges and the proposed hot air ISTW system described in (Merfield, 2012a) and (Merfield, 2012b). It is not therefore possible to directly compare the thermodynamics of the two systems, although they can be contrasted. This lack of comparability is not considered problematic, as the primary aim of the retort system is to undertake investigations of the biological effects of heating, for which the retort is considered a suitable surrogate for enclosed systems. However, a key limitation of the open retort is that moist / wet soil samples cannot be heated with hot air, because the heating is dramatically slowed due to the evaporation of the soil water into steam, which would be minimised in a closed system where the air would become saturated with steam, minimising further evaporation, although this would itself depend on initial SMC.

While the steam generator had a constant electrical power consumption, the hot air guns varied over time as they are designed to provide a constant air temperature rather than having a constant power consumption, which is why their energy consumption was averaged over 15 min during the experiment. The 7% difference between the power consumption of the steam unit and air guns (2.8 vs. 2.6 kw) is unintended and was the result of different performance of the guns during pre-experimental testing and conducting the experiment, probably due to the pre-experimental testing not including the soil in the treatment baskets in the retort which would of affected the air flow and temperature within the retort system, which the temperature regulating systems of the air guns would of reacted to during the experiment. However, this difference can be factored into the results comparing hot air and steam.

The calibration method of the infrared thermometer could also be considered basic, however, like the heating apparatus, the error in the measurement (measured by the standard deviation), and the imprecision of the timing of the manual removal of the samples once the target temperature had been reached, are considered to be sufficiently small compared to the biological effects being studied, that it is fit for purpose.

6.2. Heating time

The heating time is only a proxy for the fundamental thermodynamics, i.e., how effective the transfer of heat from the hot gasses to the soil is and then the speed with which heat moves within the soil by conduction. The data therefore comes with the caveat that it is only a guide to the thermodynamics as there are a number of unknown and uncontrolled variables, e.g., the amount of heat 'lost' during delivery, unknown pressures, gas velocity etc. To fully investigate the thermodynamics more detailed and better controlled apparatus would be required. The heating time results also need to be read in



conjunction with the germination results as these are the ultimate objective of ISTW and therefore the final arbiter of effectiveness.

6.2.1. Temperature

Although there was a clear statistical and physical difference in the heating times due to increasing temperature, this is of limited informative value because it is determined by the underlying physics and is therefore wholly expected. The key issue is if the results agree or differ from thermodynamic theory, which states that the increase in heating time with increasing temperatures should be linear up to 100°C (water's phase change temperature) as it takes the same energy to raise each soil sample by an additional °C regardless of the starting temperature. The response was generally linear, though with a small increase in time at 90 and 100°C (Table 5 and Table 6). As this effect is not large, it may be due to experimental variability, though, anecdotal observations during the experiments indicate that for steam at higher temperatures sufficient water condenses into the soil to make a visible difference to the plasticity of the soil, and therefore this extra water will increase the mass of the soil and could therefore slow heating time. Also as the soil temperature increases, the difference in the temperature of the hot gasses and soil decreases thereby affecting the rate of heat transfer. However, as the non-linearity was small it is considered that it probably would not have any practical effect, and is therefore of limited importance.

6.2.2. Aggregate size

The effect of aggregate size on heating time also needs to be compared with thermodynamic calculations as well as among the results (Table 4). As the mass of soil was the same for all samples, if all else were equal, the heating times should all be exactly the same. However, they clearly vary, with an approximately linear decrease in heating time with increasing aggregate size (the increase in aggregate size also being approximately linear), which means that less heat / energy is being absorbed by the larger aggregates. This is most likely because, as aggregate size increases, the area of its surface compared to its volume decreases (if the particles were a sphere the surface area: volume ratio would be 4.8, with higher ratios for more complex shapes). This means that as aggregate sizes increase, less of the soil receives its heat via forced convection (where soil and gas are in direct contact) and more soil is heated by conduction within the aggregates. Heat transfer by forced convection is very fast, i.e., at the speed of the gas flow (e.g., 10 cm·s), while conduction is much slower, (e.g., 0.25 - 2.18 W·m⁻¹·K⁻¹ for dry clay to wet sand (Bradford, 1995)). Therefore, as aggregate size increases an increasing volume of soil is heated by conduction from a decreasing source area. In short this means the surface of the aggregates heat up quicker while the centers stay cooler. As the infrared thermometer is reading the soil aggregates' surface temperature, not their centers, then the target temperature will be reached sooner, i.e., heating time decreases.

This is considered to be an important result as this indicates that as aggregate size increases there will be a larger proportion of soil that does not reach weed seeds' lethal temperature and therefore, as aggregate size increases weed seed survival will also increase. This is what occurred in the germination results for this experiment (see below). Further implications of these heating time results are discussed in the germination section.

This result is in agreement with Melander & Kristensen, (2011), who also found that coarse soil heated up faster, although the differences were not large and only statistically significant at 60°C.

6.2.3. Heat type

The heating times of steam and air, if everything else were equal, should be the same as the energy content of the two gases were the same. The results differ (Table 4) due to a number of inequalities in the two systems, e.g., there was the (unintended) 7% difference in input energy between the two



systems, differing energy densities and unknown factors such as the velocity of the two gases. Calculating the percentage difference between steam and hot air (Table 16) produces a confused picture.

Table 15. The percentage difference in heating times (seconds) between hot air and steam.

Aggregate size	Heat type		% difference
	Air	Steam	
1.0-2.8 mm	19.7	16.1	22%
2.8-5.6 mm	17.1	13.0	32%
5.6-8.0 mm	13.9	11.6	20%
8.0-19.0 mm	10.1	13.0	-22%
Mean	15.2	13.4	13%

The overall (mean) difference in heating time is 13% lower (quicker) for steam, which as it had 7% greater energy input means that the difference should be smaller were the energy contents of the two gasses the same (though not necessarily 7% less). However, the differences at individual temperatures do not have a clear trend and they vary considerably, which makes further interpretation difficult. Better experimental methods are needed to determine causal mechanisms.

However, in regard to the primary objectives of this research, i.e., using hot air, rather than steam, to heat soil, it is clear that hot air appeared effective at heating soil, if not quite as fast as steam. Therefore this result indicates that hot air is a viable alternative to steam for heating soil in an ISTW system, especially as there considered to be potential to improve heat transfer by varying factors such as air temperature and gas volume / velocities. However, the results of steam vs. air on seed mortality / emerged weedlings (discussed below) is very different, indicating that heating time is not a good proxy of ultimate effectiveness.

6.2.4. Soil moisture content and texture

As for the effects of the other experimental factors on heating time, the comparison of the effect of SMC with thermodynamic theory is as important as the differences among the results (Table 6 and Table 7). The specific heat of soil is about 1.2 MJ·kg·°K with slight variation, e.g., 0.1 MJ·kg·°K, depending on texture. 400 g of soil therefore requires 0.480 MJ·°K to heat up. Water has a specific heat of 4.18 MJ·kg·°K, i.e., ~3.5 times that of soil (depending on texture etc.), so it should have a disproportionate effect on the energy required and therefore heating time. Table 16 shows the calculated energy required to heat the soils used in expt. 3, using a starting temperature for the soil of 20°C.

Table 16. The amount of theoretical /calculated energy (MJ) required to heat the three soil textures at the four SMC used plus dry soil.

SMC	Texture		
	Clay	Sand	Silt
Dry	34	34	34
A	34	39	37
B	53	45	43
C	72	58	56
D	90	70	68

To compare heating times with the theoretical energy required, which are different quantities, the percentage difference is used, Table 17 and Table 18.



Table 17. The theoretical percentage increase in energy required to heat the soils in Table 16 compared with dry soil.

SMC	Texture		
	Clay	Sand	Silt
A	1%	16%	10%
B	57%	35%	28%
C	113%	72%	65%
D	169%	109%	103%

Table 18. The actual percentage difference in heating time for the soils compared with SMC 'A'

SMC	Texture		
	Clay	Sand	Silt
A	n/a	n/a	n/a
B	41%	-1%	6%
C	47%	13%	19%
D	204%	164%	14%

Table 19. The difference (in percentage points) between Table 17 and Table 18

SMC	Texture		
	Clay	Sand	Silt
A	n/a	n/a	n/a
B	-16	-35	-22
C	-66	-59	-46
D	35	55	-89

While heating time is generally in agreement with theory, i.e., higher SMC take longer to heat there is important variation among the details Table 19. All of the soils appear to initially take less time to heat as SMC increases than theory states, but for clay and sand this reverses at the highest SMC with it taking more time than calculated.

Anecdotal visual observations during treatment, was that the SMC D sand treatment appeared to become fully saturated by water as heating progressed, i.e., exceeded field capacity (due to the gaseous steam passing through it condensing into liquid water) such that the sand turned into a colloid hydrogel i.e., 'quicksand' and started to behave as a fluid. It is possible that in this state, the steam was less able to pass through the sand thereby slowing heating. The same condensation effect could also be occurring in the clay, although as clays do not form colloid hydrogels, the transition above field capacity would not be so visually obvious. This effect may therefore disappear if the highest SMC levels were slightly reduced so that the soils do not reach field capacity during heating. The silt soil did not appear to reach field capacity during treatment, i.e., no water came out of it. This clearly needs more research to confirm.

The results for expt. 2 (Table 6) are even more mixed. With the exception of the 60°C treatment, heating time initially increases from SMC A to B then decreases, completely contrary to theory which says it should always increase. In addition the effect is not consistent across the temperatures; 60°C shows a consistent increase with increasing SMC, but as temperature rises the increase and decrease effect become larger, until at 100°C there is a complete reversal with the lower SMCs taking longer to heat up than the higher SMCs.

As the soil used in expt. 2 was the same soil as the silt used in expt. 3, (though collected in slightly different locations) the 90°C column in Table 6 is therefore equivalent to the silt column in Table 7 (i.e., both are the same soil heated to 90°C at the same four SMCs, although in separate experiments). The heating times in the two experiments at SMC A and B are very close, but then diverge at SMC C and D. This would indicate that there may be experimental issues, probably with expt. 2. However, the results for the other factor of temperature are consistent with theory, and there is a general pattern in the results, rather than just random variation, which indicates there is a real effect.

Only one paper, Melander & Kristensen (2011) has been found that empirically studied the effect of SMC and texture on heating. However, the soils were both sands and only two SMC levels were used: sandy loam, 5.3% and 15.3% SMC; and sand, 3.7% and 12.8% SMC (percentages by weight), so even the higher SMC would still be considered 'dry' from an agronomic perspective, e.g., its suitability for tillage and falling between SMC B and C for sand for this experiment. Within this more limited SMC range, the dry soils were quicker to heat up than the moist soils (Table 20).

Table 20. Percentage increase in time taken to reach target temperatures of 'moist' and 'dry' soil for two soil textures, calculated from (Melander & Kristensen, 2011).

Soil type	Temperature			
	60°C	70°C	80°C	Mean
Sandy loam	4%	9%	2%	5%



The sand was also slightly slower to heat up than the sandy loam across both moisture and temperatures of 66, 75 and 83°C, with average times of 83 s for the sandy loam and 89 s for the sand. While there were differences in heating time among the soil textures in this experiment they cannot be compared with Melander & Kristensen's results due to that experiment only comparing sandy soils. However, the results of Melander & Kristensen's and this experiment show that there is a difference in heating times for different soil textures, although not physically large, and there is an interaction with SMC, which is consistent with the wider understanding of soil heating, at least at natural soil temperatures, (Hillel, 1980).

Water not only effects the specific heat of the soil, but also has a large effect on thermal conductivity within soil, and that in turn affects thermal diffusivity (the ratio of thermal conductivity to volumetric heat capacity) which initially increases with SMC but then reduces (Hillel, 1980). It is possible that this effect could at least partly explain this result. However, much of the work on thermal transfer within soil has been focused on soils in natural conditions, rather than the artificial heating systems used in this experiment where heat is transferred to the soil via forced convection to the surface of soil aggregates and particles, which may diminish the contribution of conductivity and diffusivity. It therefore appears that the effect of SMC on the heating process is considerably more complex than basic theory indicates. Therefore no overall interpretation of this result is offered, but it is clear that more detailed research and better theoretical understanding are required. However, as noted in section 5.2 the open retort heating system is fundamentally different to closed heat exchangers, so the results for such systems could be different again. Progressing to closed heating systems, ideally continual flow, as proposed in Merfield (2012b) is considered important so the results reflect how the proposed field-machine designs would work.

6.3. Weedling emergence

The effect of soil heating on weed emergence, i.e., the proportion of weed seeds that survive thermal treatment and that then germinate and emerge, is considered the key measurement of success, as achieving 100% seed kill and therefore eliminating therophyte weeds emerging in the crop row is the primary objective of farmers and growers using ISTW.

However, on this measurement of success these results could be considered less than successful as even at the highest treatment temperature of 100°C weeds still emerged. However, while the results may not be an outright success, they do give clear indications as to the effects of temperature, SMC, aggregate size and heat type on seed mortality and therefore progress the fundamental understanding of the processes, and therefore where future work needs to be targeted.

6.3.1. Temperature

The response to increasing temperature was generally linear for both expts. 1 and 2 (Table 8 and Table 11). This is as expected as increasing temperature is increasingly lethal to weed seeds and therefore the percentage emergence should decline. The higher emergence of expt. 1 is considered only partly due to the effect of the larger aggregates, as there were still 17.3% emerged weedlings at 100°C at 1.0-2.8 mm aggregate size compared with the control. The larger part of the difference appears to be due to the difference between hot air and steam (discussed below), with hot air resulting in considerably higher weedling emergence than steam.

Other researchers have reported much higher seed mortality at these temperatures. van Loenen et al., (2003) used an "aerated steam" system, that is perhaps better described as humidified hot air, where air was circulated through a heater (that determined the temperature) that then had hot water sprayed into it, the resulting air / water vapour mixture then passed upwards through the soil sample, before



circulating back to the heater. They found that *Chenopodium album* seeds were killed between 60 and 65°C depending on whether they were dry or imbibed with seed death defined as the point when all four replicates had no emerged weeds. However, the soils were at 70% of field capacity and heated for three minutes followed by an additional seven minutes 'resting time' in the test-rig during which time "the temperature stayed very close to target temperature" (van Loenen *et al.*, 2003). Total treatment time was therefore 600 s, the soil had a high SMC, and a high humidity heat source was used.

In comparison, Melander & Jørgensen (2004) used a laboratory rig that injected saturated steam via small pipes into soil held in an 70 mm wide and 80 mm deep insulated trough. The steam dose was determined by treatment time, approximately 70 s of heating achieved 60°C while 210 s were required to achieve approximately 80 - 95°C and then the soil was left in the trough for an additional 600 s. Total treatment time was therefore between 660 and 720 s. SMC was between 7 and 9% by weight. A second experiment varied the removal time between 300 and 1,200 seconds giving total treatment times between 300 and 1,200 s, however, this did not produce significant results so the data was not presented. Curves were fitted to the data, with temperatures ranging for 20 to 95°C, resulting in sigmoid curves. These showed, across a range of weed and surrogate weed species, that the first inflection point (where seed started to die) was between 40 to 50°C and the second inflection point (where most seeds were dead) was between 60 and 80°C. However, Melander & Jørgensen were measuring the 95% mortality level / 5% emergence, rather than zero emergence across all reps as used by van Loenen *et al.*, (2003). The fitted curves presented by Melander & Jørgensen (2004) indicate that 100% seed mortality, as defined by van Loenen *et al.*, was only achieved around 90°C.

In subsequent work Melander & Kristensen (2011) further studied the effect of duration in terms of varying cooling down periods. They used an enclosed metal cylinder (70 mm long and 158 mm internal diameter) with a mechanical stirrer to heat the soil and "sprayed" steam into the cylinder / soil to heat it, to 50, 65 or 80°C and cooled it to 40°C by either blowing cold air in at two rates or the soil was left to cool in the cylinder without cold air injection, to give three cooling durations. Heating times varied from 3 to 12 s depending on target temperature and the cooling times varies from 100 to 776 s giving total treatment times of 103 to 788 s. Despite this they found no effect of cooling on weedling emergence.

In these experiments heating times varied from 8 to 24 s in expt. 1 (Table 5) and 21 to 64 s in expt. 2 for temperatures between 60 and 100°C (the difference between experiments is due to the smaller weight of soil used in expt.1.) The exact cooling time was not measured in this experiment, but, in pre-experimental testing using the probe thermometer cooling time was rapid and approximately less than 10 s. Total treatment times for these experiment range from approx. 18 to 74 s.

Treatment durations among all of the above research therefore vary widely, including both treatment time and 'cooling' / post-heating time, as well as the rate of cooling, or lack of cooling, during the post-heating period. Overall these results show are considered to show that the longer the soil and seeds are at the treatment temperatures, the lower the maximum temperature required to achieve complete weed seed death. This is considered to be in agreement with the 'five temperature zones' theory outlined above and proposed in (Merfield, 2012a). Treatment temperatures above 40°C and up to the maximum of 100°C therefore appear to be in zone 4 - the semi hot zone, i.e., where there is a temperature × duration interaction.

It is hypothesised that this effect could be an example of a thermal time effect, also referred to as 'growing degree days' or 'heat units' that is used in predictive models of crop growth and seed germination. It is therefore proposed that a thermal time model, using a base temperature around the start of the first inflection point of the temperature response curves, e.g., approx. 40°C, may be able to better model / predict seed mortality for the interaction of temperature and treatment duration, including cooling down periods than maximum temperature alone. If a thermal time model of seed death is as accurate as some of the thermal time models used for crop growth etc., then this could be of



considerable value in accurately predicting the necessary treatment conditions needed to ensure complete seed death for real-world ISTW treatment.

6.3.2. Soil Moisture Content

The effect of SMC on the emerged weedlings as a percentage of the controls is unambiguous in showing a substantial reduction in weedlings with increasing SMC, with a slight increase in the effect as temperature increases (Table 11), e.g., at 60°C there is a 79% reduction in weedlings between SMC A and D while at 100°C there is a 90% reduction.

However, a caveat is considered necessary trying extrapolate this result to SMC in general. The soil used in this experiment was initially air dried in a warm glasshouse to the low SMC of 3.3%, and then wetted 48 hours prior to the experiment. The standard reaction of non-dormant weed seeds to a period of residing in warm dry soil that is then rapidly wetted, is to start germinating. Forty eight hours is considered sufficient time for the weed seeds to have fully imbibed (typically < 24 hrs) and started the germination process, but without emerging from the seed. If the weeds had emerged the experiment would not of been testing the effect of soil heating on seed mortality but rather seedling mortality. It is considered that seedlings would be much more susceptible to heat than seeds, however, a seed that has started to germinate, but not yet emerged, is also considered to be more susceptible to heat than an ungerminated or dormant seed, as the germinating seed has irreversibly activated a wide range of biochemical and biophysical pathways, many of which could be sensitive to heating. If in comparison, soil had been used that had been cold and wet for an extended period, e.g., as if over-winter, then the seeds would not have received the germinating impulse that they did when warm dry soil was wetted. Therefore, seeds in this situation, i.e., moist, but not having initiated germination, may have a higher resistance to thermal treatment. It is this latter situation, i.e., soil that has been moist and cool for an extended period (e.g., weeks to months) prior to treatment is considered to be the more likely situation for ISTW in real-world farming, i.e., in spring prior when soils are cold and wet from winter. Clearly a fuller picture of the effect of SMC on seed mortality needs to replicate the real-world situation, i.e., soils need to be collected during winter in a natural moist state, with some slowly dried at cool temperatures (e.g., < 10°C) to the lower SMC, and then treated.

Only one other paper has been found studying the effect of SMC on weedling emergence, Melander & Kristensen (2011). They studied the effect of two soil moisture levels in two soil textures (details above) on heating time and emergence. While the results on heating times were clear (discussed above), the effect of the two moisture levels on seedling emergence, were not, with only total seedling emergence being statistically lower for the dry sandy loam (Melander & Kristensen, 2011). However, as noted above, the difference between the two SMC levels was comparatively small, with a difference of approx. 10 percentage points and a maximum SMC of 15%. This contrasts with the maximum range in this study of 45 percentage points and a maximum SMC of 50%. SMC A and B used in this study are approximately comparable with the two SMC of Melander & Kristensen (2011), and contrary to their results, this study found a biologically large and statistically significant difference in emergence between these two SMC (Table 11). However, as argued above, the method by which the target SMC are achieved (e.g., wetting dry soil, vs. drying wet soil) could have a significant effect on the results. Melander & Kristensen do not give details of the wetting process, other than stating that the soils were collected two days prior to the experiment and the moist sample was watered, without giving a time frame between watering and treatment.

It was hypothesised above, that thermal-time models may be able to better predict the results of heating than temperature alone. It is further hypothesised that considering the significant effects SMC has on seed mortality, hydrothermal-time models (Gummerson, 1986; Bradford, 1995) may be of value by taking into account the role of water as well as temperature and time in seed death.



Hydrothermal-time models also point to another factor that could affect seed mortality with increasing SMC, in that at higher SMC, germination is faster. The seeds in the soils with the lowest SMC, especially in expt. 2 where the SMC was 3.4%, may not have started germinating due to insufficient water, while those at the highest SMC may have rapidly started germinating. Therefore, following the arguments above, regarding germinating seeds' increase susceptibility to heat, these results could be as much a comparison of germinated and ungerminated seeds as seeds in soil at a range of SMC. The above arguments about other methods for manipulating SMC, i.e., starting with the soil cold and wet, rather than warm and dry, could be even more critical, and that the role of germination initiation, as a factor distinct from SMC, may need to be considered.

Based on this limited data and considering the theoretical complexities, it is not possible to draw firm conclusions as to the causal effects of SMC. In addition the results from this research on the effect of heat type, i.e., 'dry' hot air vs. 'wet' steam showed steam killed more seeds / have lower weedling emergence (see below), indicating that the effect of moisture in ISTW is even more complex. A substantial amount of additional work is therefore required.

6.3.3. Heat type

On an 'all other factors being equal' basis, thermodynamic theory states that if the hot air and steam have the same energy content, then their effect on soil heating should be the same and therefore their effect on seed mortality should also be the same. This is clearly not the case, with a very significant difference in emerged weedlings between air and steam (Table 10). On the face of it, this is not a good result for the use of hot air for ISTW.

It is not believed that the difference can be attributed to the limitations of the experimental setup, e.g., the 7% lower in energy consumption of air compared with steam, as the difference between weedlings for steam and air is so large (413%) compared with the difference for heating time (13%).

One cause could be a difference in the effect of heating time and aggregate size, e.g., the hotter air heated the surface of the soil aggregates and particles quicker, thereby creating a 'false' temperature reading for the overall / average temperature of both the surface and centers of soil aggregates and particles. However, the interaction of aggregate size and heat type was not statistically significant and physically small (Table 4) which, along with the similar heating times, indicates that differential speed of heating soil particles and aggregates between steam and air is probably not the cause of the large difference in weedlings.

In comparison, there was a large effect of SMC on weedling emergence (Table 11), although with a number of caveats as to the cause, as discussed above. Steam by its nature contains appreciable amounts of water, initially as a gas (steam) but on contact with the cooler soil, the steam condenses into a liquid, which increases SMC. Condensation is also a key step in steam's highly effective heat transfer ability, due to the very large latent heat of condensation of water. In comparison, the 'dry' heat of hot air, will be vaporising the small amount of remaining water in the soil as it is heated, which produces a small cooling effect (which could account for some of the 13% difference in heating time), but, this does not appear to explain the large difference in weedling emergence.

However, it is known that seeds have higher survival rates in dry compared with 'wet' heat. For example, Bloemhard et al., (1992) found that saturated steam killed *Abutilon theophrasti* Medic. seeds at temperatures that they survived when treated with dry heat. Tenente et al., (1999) comparing hot water with dry heat for nematode eradication on rice, maize and oat seed used lower temperatures (approx. 20°C lower) and lower durations (approx.. 30 min vs. 6 hours) when using dry heat to gain a similar germination results. Mendes et al., (2001) used a dry treatment of 60°C for 3 or 6 h followed by 90°C for 3 or 6 h while the water bath treatment used 40°C for 10, 20 or 30 min followed by 50 or 60°C for 10, 20 or 30 min, for control of *Fusarium oxysporum* in alfalfa (*Medicago falcata* L.).



The research is therefore clear that the water content of the heat source has a clear effect on seed survival: what is less clear, is exactly why. A common explanation, is that the moist heat sources heat the seeds quicker. However, most cropping weed seeds are small, e.g., < 1 mm, so the volume of the seed is small compared with its surface area, and the distance from the surface to the centre is also small so the seeds should heat up and equilibrate with their surroundings very quickly, e.g., in a few seconds to tens of seconds. As heating times are typically for durations of minutes to hours even days, the large differences in mortality between dry and moist heat sources is not therefore considered to be due to more rapid heating as the few additional seconds required to reach the target temperature with dry heat is a tiny proportion of overall heating time. There may also be direct effects of water on the speed of conduction within the seeds, just as there is a large effect on the rate of conduction between moist and dry soils. However, the key driver of this effect in soil is the substitution of water for air (Hillel, 1980), while in seeds, water is not displacing air (it is rehydrating the cells) so it not possible to assume that water will have the same kind of effect on conduction as it does in soil. Further, the size issue also comes into play, in that even if moist seeds conducted heat much faster, e.g., doubling the rate, the small size of weed seeds means that this may only reduce heating times by a few seconds out of total heating times of minutes to hours indicating that it is less likely to be the cause. In addition, where dry seeds are being heated with wet heat sources there is unlikely to be time for the seeds to absorb much water during heating durations of tens of minutes.

However, a wide range of experiments clearly demonstrate that there is a clear effect of moisture on seed mortality, so if the effect is not due to speed of heating, another cause is required.

An alternative hypothesis is that there is a direct biophysical effect of moisture on seeds. For example, as water is heated it expands, which can cause cellular damage, such as bursting cell walls (Parish, 1989) that may not occur when the seed is in a dry state. However, for this concept to work, when dry seeds are heated with a moist heat source, the water must rapidly penetrate the seeds to have any effect. However, seeds have evolved hard casings that are only slowly permeable to water, and in instances such as hard-seeds, they are effectively impervious. But, the difference between steam and air extends even to hard-seeds e.g., the *A. theophrasti* tested by Bloemhard et al., (1992) was hard seeded and steam achieved significantly greater seed mortality. However, seeds have evolved to cope with soil temperatures, and not the temperatures used for seed disinfestation or killing. These higher temperatures may result in changes to the seed they have not evolved to cope with, for example, initial thermal expansion of the dry seed makes the seed coat more porous, which may then allow moisture into the seed, which then accelerates the damage. However, if such effects are real, they need to happen very quickly.

There is also the question of the relative contribution of moisture in the heat source vs. moisture levels in the seed or its surroundings, e.g., soil. For example, while this research showed a large difference in seed mortality in dry soil, that difference may no longer exist when the soil and therefore seeds start out at high moisture contents. The issue of the soil condition prior to treatment, i.e., dry and warm then wetted, vs. cold and moist and then dried, discussed above, may also affect the outcome. Unfortunately due to the limitations of this experimental setup, i.e., open retort, the effect of hot air vs. steam on seed mortality in moist soil could not be compared, which is considered vital to better understand this issues.

Therefore, the issue of both soil and heat source moisture clearly needs a considerable amount of additional research to be fully understood and addressed especially if hot air is to be used for ISTW systems.

6.3.4. Aggregate size

The hypothesis that larger aggregates would reduce seed mortality due to protecting the seeds from the heat is clearly supported by the emerged weedling results with a 37% reduction in weedlings from the largest to smallest aggregate size (Table 9). The hypothesis that the larger aggregates would protect



weed seeds from the heat is compounded by the heating time results which show that larger aggregates also absorb less heat. Therefore, increasing aggregate size is therefore doubly detrimental to effective ISTW.

Only one other paper has been found that has studied the effect of aggregate size on seed survival / weedling emergence, (Melander & Kristensen, 2011). It was found that the coarse soil heated up faster on an overall average of 9% across the three temperatures. There was an 18% overall increase in weedlings from the coarse soil, although with differences among species, and with the total numbers being low, the difference was not statistically significant. This result is in general agreement with this research (despite that lack of statistical significance) and also therefore indicates that large aggregates will decrease seed mortality.

Some means of taking into account the effect of aggregate size on the treatment process, e.g., duration, will therefore be required. However, soil temperature, may not be a good guide, as shown by the heating time results, as both contact and infrared thermometers would only measure aggregate surface, not internal temperature, which is the critical value. No further ideas as how this could be managed are suggested at this point so it is clearly an area that also needs further research.

6.4. Bulk density

It is noted that the bulk density measured in this experiment is not the same as the standard measurement of bulk density of in-situ soil. Forcing the soils through a sieve after collection would have affected bulk density and possibly helped reduced the differences among the three soil textures as the maximum aggregate size would be the same. However, as the aim was to compare among the soils in the experiment, rather than have an 'absolute' value that is comparable with independent measurements, the lack of external comparability is not considered a significant issue. Despite this, the bulk density figures in this experiment are not too dissimilar to typical bulk density figures given for the three textures in textbooks, e.g., 1.3-1.7 g·cm³ for sands and 1.1-1.6 g·cm³ for silts and clays (Brady & Weil, 2008).

All the textures showed a general increase in bulk density from the untreated control to the highest SMC, with the exception of the untreated sand control having a higher density and the clay SMC 'C' which showed a small reduction compared with the next lower SMC 'B' (Table 12).

While the change in bulk density does not appear great, with the density increasing from the control to SMC 'D' in clay by 11% and 10% for silt, and by 5% in sand from SMC 'A' to 'D' (i.e., ignoring the control) in physical terms the effect was substantial for silt and clay with the untreated control and lower SMC still retaining obvious structure while at the highest SMC structure was effectively destroyed (sand showed no effect as it had no structure to start with).

In addition, at the higher SMC the soils contained a considerable amount of water, for example, 181 g of water was added to the 400 g of clay, to achieve the 'D' SMC i.e., the weight of water was just under half the weight of the soil. On a volume basis, water is 1 g cm³ and the soils ranged from 0.4 to 0.48 g·cm³ i.e., just over half the density of water, so, for the above clay example the water represented about ¼ of the volume of the clay, but resulted in a higher density, i.e., smaller volume than the clay without water. This is considered a clear illustration of the critical role of water in soil bulk density and compaction.

The reason for the untreated sand having a higher density than the lower SMCs is unknown, but as there is a clear trend in the data the effect is considered to be real and of scientific interest. However, from a practical perspective the effect is considered to be of little importance as the untreated sand and sand with the highest SMC had similar densities so ISTW treatment at the highest SMC would leave a sand soil at the same bulk density that it started with, i.e., unchanged.



The lower result for clay at SMC 'C' is contrary to the general trend for clay and for all the soils. This result may therefore be an anomaly. Further, the crush weight, which is the more important measurement, do show a consistent trend.

6.5. Crush weight

While the numerical differences in bulk density among the soils and SMCs do not appear great, the differences in the crush weights is considered dramatic (Table 13). As hypothesized, sand does not form strong aggregates, and definitely not clods, so even at the highest SMC only 3.7 kg was required to crush the soil cylinder. At the other extreme clay required 1.3 tonnes to crush the soil cylinder for the highest SMC, clearly a very compact clod! Silt, though not forming as strong a cylinder as clay still required a substantial 0.8 tonnes to crush. This is considered a very unambiguous demonstration of the dramatic differences in structure among the three soil textures, and that heating and/or mixing clay and silt soils at higher SMCs where soils are in a plastic state, and then compressing them, can result in severe compaction / dense clods. While this is common knowledge among farmers who work such soils, and soil scientists, i.e., it is not truly new information, it does highlight the critical importance of taking a range of soil textures into account when designing ISTW machinery.

6.6. Final weights

The weight of the soil cylinders after drying are all below the 400 g starting weight (Table 14) which is to be expected as the soil drying cabinet is considered to more effective at drying soil than placing soil in a glasshouse, where humidity may have been higher, for example. In addition small amounts soil was inevitably lost during the heating, mixing, and compacting process, especially at higher SMC and particularly for clay and silt which stuck tenaciously to the treatment equipment. This is reflected in the decreasing weights for higher SMC. The final weight therefore provided a useful check that the soils were dry, especially the very compact silt and clay cylinders and that excessive amounts of soil were not lost during processing.

6.7. Conclusions

The overall objectives of these experiments were to gain a deeper understanding of the role of temperature, soil moisture, aggregate size and soil texture on ISTW, to optimise real-world ISTW systems to ensure 100% weed seed death while minimising energy / fuel consumption and to point to where further research is required for the development of heat-recycling, hot-air ISTW machinery.

While the temperature results appear confounding, as seed mortality differs from other research, it points to the importance of the temperature $\times$ heating duration interaction, which led to the hypothesis that a thermal-time model, similar to those widely used for predicting crop growth and seed germination, may be required. It also indicates that for rapid heating and cooling, as would be used in the proposed heat-recycling, hot-air ISTW system (Merfield, 2012b), that temperatures higher than 100°C may be required to achieve seed death over short durations. Future research therefore needs to include higher temperatures, e.g., as high as 150°C at short durations, e.g., < 60 seconds total heating time, as well as determining if thermal-time gives better predictions of seed mortality than maximum temperature. Using a variable power heat source to achieve a range of treatment temperatures while keeping treatment duration fixed, may also provide useful information on the interaction of temperature and duration that would inform or could be used to test thermal-time models.

The results for soil moisture in this, other ISTW research and research into disinfecting crop seeds of pests and pathogens, indicates that it has a pivotal role in seed death, which led to the suggestion that hydrothermal-time models may be better than thermal-time models used in seed germination. However, it was also argued that different ways of achieving a given SMC, e.g., cool drying of soils that had been cold and wet, vs. wetting soils that had been warm and dry, could produce contrary results,



due to differing effects on inducing germination. This indicates that simply copying the hydrothermal time models used for germination may not work. It also appears that higher moisture levels in the heat source and their environment, e.g., the soil, may also have direct negative effects on seeds, even if the seeds are dry at the start of treatment and/or are hard-seeded. Further research is therefore required to pick apart the different contributions moisture has in (1) aiding heat transfer (2) having a direct biophysical effects on seeds, and (3) inducing germination, in terms of both the effectiveness of the heating process, and particularly on seed mortality / seedling emergence.

Fortunately in terms of real-world ISTW, it is envisaged that most of the producers for whom an ISTW system would be economic are growing higher value crops where irrigation is used, which can also be used to moisten fields to optimum SMC prior to ISTW treatment. It is not however considered practical to apply the water as part of the treatment process due to the large quantities needed, e.g., for four crop rows in 1.8 m beds, with 70 x 70 mm width x depth soil treatment area for each row, 1,500 kg·m³ soil density, and adding 0.20 kg of water per kg of soil to raise SMC from 5% to 30% would require approx. 32,700 L water·ha⁻¹. These kinds of volumes are considered best applied via irrigation. In addition the elevated SMC would also be required for optimum crop seed germination post ISTW treatment, and the whole field, not just crop rows, would need to have its moisture increased.

Aggregate size in this study and Melander & Kristensen, (2011) has been shown to absorb less heat due to increasing volume to surface ratio and also increase seedling emergence, probably due to seeds within the centers of aggregates being protected from the heat. This is considered a particular problem for heat-recycling, hot-air ISTW systems as these will be rapidly heating and cooling the soil, so providing less time for the heat to move by conduction within soil aggregates. The thermal solution to aggregates is to lengthen the heating process so that the soil in the centre of aggregates has sufficient time to reach lethal temperatures x durations, however, slowing the heating process is the opposite of what is required in real-world ISTW systems where work rates are likely to be critical for producers. The alternative is therefore to reduce aggregate size, either via pre-ISTW tillage, or including tillage type equipment on the ISTW machinery to ensure the crop row soil has a sufficiently fine tilth.

The interaction of soil moisture with aggregate size may also be an important as it is generally considered that higher SMC increases the rate of heat transfer within soils (Hillel, 1980), however, the results from these experiments indicate a more complex situation. Future research therefore needs to investigate the interactions of heat type, thermal-time, SMC and aggregate size on seed death.

The differences among the three soil textures for bulk density and particularly the production of hard clods that resist crushing in the silt and clay soils at the higher SMCs is unambiguous. This is to some extent in conflict with the effects of SMC on seed mortality where higher SMCs appear to be beneficial. Clearly, ISTW machinery will have to be designed to minimise the amount and intensity of soil mixing / tillage to levels just sufficient for effective soil / gas contact for heat transfer, and, compaction should be minimised. Being able to cope with sticky soils will also be required, as while it may not be ideal to treat silt and clay soils at higher SMCs, the necessities of practical farming require it, especially as many of the crops that would benefit from ISTW are likely to be spring sown vegetable crops, a time of year when soils are often wet from winter.

Prior to the experiment there was a concern that even at lower SMCs sufficient steam would condense into the soil that it would raise the SMC to a level where the soil became plastic and therefore at risk of compaction, as happens with whole-soil steaming (Gay *et al.*, 2010a, 2010b). The short duration of heating in this experiment (< 1 min) did not result in the soils becoming very wet, however, these anecdotal observations need to be experimentally verified. However, this is probably more of scientific value, as this experiment as a whole has shown, heating and tilling soils at high SMC has considerable detrimental effects on their structure and therefore should be minimised in real-world farming. At the same time, a hot air ISTW system will not increase SMC, and would more likely cause a small decrease as



some soil moisture would evaporate during treatment and be carried out of the treatment system by the airflow. This could be an additional benefit of a hot air over a steam based system, which would need experimental confirmation.

It is noted that while the ultimate concern of expt. 3 is that the compaction of wet clay and silt soils during ISTW treatment would have a highly negative effect on crop growth, the experiment has not directly made that link, i.e., it has only shown the effect of ISTW on soil physical properties, not the subsequent effect on plant growth. While this is a methodological flaw, the effects of compaction on plant growth are so well established, both in the scientific literature, and as common knowledge among farmers and growers that manage such soils, that experimentally establishing this link is considered unnecessary.

It is also noted that expt. 3 studied the combined effect of heating and tillage. It is not possible to determine the relative contributions of heating and mixing had on compaction. While this is a valid, and possibly interesting, issue from a methodological and scientific perspective, it is not considered particularly relevant to the primary issue that this experiment was designed to highlight, i.e., that clay and silt soils behave quite differently to sands in terms of the effect of ISTW treatment on soil structure, especially at higher SMCs. So while methodologically and scientifically this is an unanswered question, from the perspective of improving ISTW machinery, further work on this issue is not considered warranted.

The different soil textures also had different heating times, though while statistically significant it was not physically large, being smaller than the differences due to SMC and aggregate size. Variation in heat absorption and transfer among different soil textures is well known but due to the complexity and interaction of the multiple factors / processes involved, only partial modelling is possible (Hillel, 1980). The impact of this variation on seed mortality needs to be studied further, as the small difference in heating time between air and steam resulted in very large differences in weedling emergence, however, this was probably due in part to the low SMC of the soils in expt. 1. Other research found that soil texture had little effect on the mortality of added seeds (Melander & Kristensen, 2011). It is possible that when a thermal-time approach is used, it compensates for different heating responses of different soil textures, which in turn highlights the issue of continual monitoring of soil temperatures during treatment to provide a feedback / control system to ensure target temperatures are met, as discussed in (Merfield, 2012a, 2012b).

Overall, SMC and aggregate size appear to be the critical soil factors influencing the effectiveness of ISTW and that potentially, thermal-time (or possibly hydrothermal-time) models may be better predictors of seed mortality than maximum temperatures alone. The key difference between hot air and steam systems is water content (moisture) and it appears, like SMC, that this is the critical factor that needs to be addressed in heat-recycling, hot-air ISTW systems, potentially by ensuring optimum SMC levels prior to treatment. Overall, there is clearly a significant amount of further research required on the fundamentals of rapid soil heating for killing weed seed.

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