# Expanding the Potential of Intrarow Soil Thermal Weeding.

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# Executive summary

- Globally, herbicide based weed management is facing the triple threats of herbicide resistance, dwindling discovery and legislative prohibition, to the point that leading weed scientists are proposing a post-herbicide era.
- It is therefore vital that non-chemical (non-herbicide) weed management techniques are rapidly expanded.
- Intrarow soil thermal weeding (ISTW) is potentially unique among non-chemical weeding tools, in that it is a direct replacement for herbicides and it can outperform herbicides efficacy.
- ISTW works by killing the emergable weed seedbank in the intrarow, thereby completely eliminating therophyte weeds from the crop row, for the entire length of the crop production cycle. As it is applied prior to crop establishment, it works with any (row)crop.
- However, current ISTW machine designs use steam as the heat transfer media, which considerably increases the mechanical complexity, size, cost, etc., of the technology, and they use large quantities of fossil fuels.
- This report analyses the current ISTW technologies, and proposes using hot air as the transfer medium to address the mechanical complexity issue, and more critically, to allow recycling of the heat in the treated soil so potentially significantly reducing energy / fuel use.
- It also analyses the potential to use renewable fuels to replace fossil fuels, showing that vegetable oil and biogas (methane) are mechanically simple to substitute for diesel and natural gas (respectively) and as these are also among the most common farm produced biofuels their uptake is not inhibited by supply issues, although cost is still a factor.
- The synthetic literature review section identifies a number of key parameters / variables affecting the efficacy of ISTW, which are:
    - Soil and seed moisture;
    - Soil aggregate size;
    - Temperature.
- Experiments were therefore undertaken to further study these effects. These found that:
    - Moisture has multiple interactions including higher moisture increasing seed death, increasing the energy required to heat soil and, for silt and clay soils, facilitating a loss of soil structure, potentially leading to severe compaction.
    - Increasing soil aggregate size resulted in decreased weed seed kill;
    - Temperature alone is not a good predictor of seed death and that thermal time (treatment temperature × heating duration) is likely to be a better predictor.
- The research also found that hot air was an effective medium to heat soil, however, weed seed mortality was lower than for steam, possibly due to the lower moisture levels of hot air, but also possibly due to other unknown factors.
- The outcome of this report is to provide a theoretical underpinning for the construction of prototype hot air recycling ISTW machinery with the ultimate aim of agricultural machinery manufactures producing farm-ready machines for farmers and growers to use.

# General introduction

Intrarow soil thermal weeding (ISTW) is an emerging concept and technology for the management of therophyte weeds in row crops. It works by using heat to kill weed seeds in the soil (the weed seedbank), in the crop row (the intrarow) to the maximum emergence depth of most cropping weeds (about five centimetres). This means that it can eliminate therophyte weeds from the crop row and as treatment takes place prior to crop establishment, it can be used with any crop. Further, as the entire emergable intrarow weed seedbank is eliminated, the intrarow will remain weed free until fresh weed seed is introduced by tillage and/or seed rain. If these are prevented the 'residual' period of the treatment can be for the entire duration of the crop, including biennial crops. ISTW is therefore, unique among non-chemical weed management tools in that it is a direct replacement for herbicides and can outperform them, without the environmental and health risks associated with the xenobiotic chemicals that make up herbicides.

The aim of this report is to promote this potentially valuable and unique concept and to address the key problems it currently has, namely high fossil fuel consumption and mechanical complexity, by proposing a hot air recycling system and determining which renewable fuels are best to replace fossil fuels.

The report is divided into four sections:

1. A synthetic literature review and discussion of the concept and current technologies.
2. A proposal to use hot air in place of steam and to recycle the heat from the soil.
3. An analysis of renewable fuel options and energy efficiency.
4. Research experiments looking at the effect of heat type (steam vs. hot air) temperature, heating duration, soil aggregate size, soil moisture content and soil texture on ISTW effectiveness.

This information aims to provide a springboard for the production of prototype hot air recycling ISTW machinery to research the engineering required and refine the treatment parameters with the ultimate aim of agricultural machinery companies manufacturing machines that can be purchased by farmers and growers.

While this report is written for a general audience, and therefore does not include detailed engineering calculations, it assumes a reasonable level of technical understanding of both fields, and therefore uses a number of technical terms / covers technical concepts that are well established scientific knowledge, without providing an initial explanation. If the reader is not familiar with these terms many standard tertiary reference sources, e.g., encyclopaedias and particularly Wikipedia can provide the necessary background information.

# Section 1.
# A synthetic literature review and analysis of the potential for using hot air in place of steam

## 1. Summary

- Herbicide based weed management is facing an uncertain future due to the triple challenge of evolved resistance, few novel herbicides being discovered and increasing societal and legal restrictions.
- Non-chemical (non-herbicide) weed management techniques are therefore going to be increasingly important.
- Intrarow soil thermal weeding (ISTW) involves heating the soil in the intrarow (crop row) only to the depth of therophyte weed seedling emergence, thereby eliminating the emergable weed seedbank from the crop row providing 100% control of therophyte weeds for all row crops for the duration of the crop. No other form of weed management, chemical, biological or ecological can achieve this.
- However, the current ISTW approach 'band steaming' appears to be at the limit of thermal efficiency, yet considerable amounts of fuel, e.g., 500-700·L·diesel·ha$^{-1}$ are still used.
- The use of steam also creates a number of practical (e.g. the use of tonnes of water) and safety problems (use of pressurised steam boilers).
- Hot air has the potential to replace steam as the heat transfer medium for ISTW, which may also allow the recycling of heat from the soil, which is considered the only way for the efficiency of ISTW to be significantly improved.
- However, the research literature on ISTW is small and only a small number of farmers are using the technique.
- There is a need for a range of research to confirm the fundamentals of ISTW, determine if hot air based ISTW is feasible and to maximise its energy efficiency. This includes:
  - Improving the reliability of achieving 100% seed death by using higher temperatures, e.g., 90°C.
  - Confirming if maximum temperature, or determining if the interaction of temperature and treatment duration is the primary predictor of seed death.
  - Determining the extent of the role of soil moisture on seed death, particularly at higher temperatures, e.g., 90°C.
  - Determining the role of soil aggregates in providing refugia / protecting seeds from heat, again, especially at higher temperatures, e.g., 90°C.
  - Determining if heating and mixing, silt and clay soils, especially when moist, results in compaction that would affect crop performance.
  - Determining the importance of soil mixing to ensure all of treated soil achieves the target temperature.
  - Research into the direct effects of band steaming and hot air ISTW on crops in the absence of weeds.
  - Determine if hot air is a mechanically and practically viable means of soil heating for ISTW.
  - Determine if it is possible and economically viable to recycle heat from soil in a hot air ISTW system.
  - Studying the long term physical, chemical and biological impacts on soils from ISTW, both positive and negative.

# 2. Introduction

This review provides an over-arching synthesis of intrarow soil thermal weeding (ISTW): it start with a review of the context to show why ISTW and other non-chemical weed managements will be increasingly important, and then analyses ISTW from a thermodynamic perspective and then compares ISTW research with thermodynamic theory to identify gaps, issues and where information is lacking.

## 2.1. The end of herbicides?

Herbicide based weed management has been the almost exclusive form of weed management in the developed world's agricultural systems for around half a century. While initially successful in the core objectives of simplifying and expediting weed control, non-target effects and evolved resistance, have become increasingly evident. This has in-turn lead to increased legislative restrictions on herbicide use (and other xenobiocides), and a growing list of resistant weeds which are no longer controlled by one or more herbicides, particularly since the introduction of transgenic herbicide resistant crops (Harker *et al.*, 2012). At the same time the rate of new herbicide discovery and translation into legally acceptable end-user products has continued to decline from a peak in the 1980s (Anne R Thompson, Dow AgroSciences Ltd. pers. comm.). This nexus of increased legal restrictions and weed resistance plus declining replacement herbicides indicates that non-chemical weed management will be required to play an increasingly important role in the future, to the point that authoritative sources have suggested we may be facing a post-herbicide future (Marshall, 2010).

## 2.2. Non-chemical weed management

Weed (and other pest) management can be divided into four sub-disciplines:

- Physical (mechanical)
- Chemical
- Biological
- Ecological (cultural)

From this perspective non-chemical weed management can be achieved through physical means, such as mechanical hoeing and thermal weeding; biological techniques, such as classical biological control via the introduction of a weed's natural enemies; and ecological methods, i.e. manipulating the interactions among species, e.g., rotations.

While many of these non-chemical methods can be highly effective, they are often more complex to implement and slower acting than herbicides. However a few non-chemical techniques can perform on a par, or even outperform herbicides.

## 2.3. Intrarow soil thermal weeding - better than herbicides?

Intrarow soil thermal weeding (ISTW) is a technique that can rival herbicides in terms of its simplicity and expedience. Perhaps the 'holy grail' for residual herbicides would be a product that is:

- broad spectrum, i.e. kills practically all weeds;
- had a residual period as long as the crop's production cycle;
- could be used in any crop;
- had a nil withholding period;
- had no risk of releasing xenobiotic materials into the environment;
- had exceptional reliability levels (i.e., always works); and
- had no risk of evolved resistance.

However, this is impossible at both a practical and theoretical level. In comparison, ISTW can achieve these objectives, as it can control all therophyte weeds, it can last for the full duration of annual and biennial crops (i.e., its 'residual' period), it works for all (row) crops (i.e., it is akin to a selective herbicide), it uses no xenobiotics so has no withholding period or has any risk of releasing xenobiotic materials and there is always a lethal thermal limit for all organisms, due to heat causing multiple and widespread biological damage (unlike the single biochemical point of action of herbicides), so it is both highly reliable and is not considered possible for weeds to evolve resistance.

It is therefore considered important that ISTW is more widely appreciated and some of the current problems are addressed.

# 3. Intrarow soil thermal weeding

## 3.1. Origins and explanation

ISTW using steam was pioneered in the early 2000s in Denmark by Melander et al. (2002b) and has continued to be researched (Melander *et al.*, 2002a; Melander & Jørgensen, 2003; Hansson & Svensson, 2004; Jørgensen *et al.*, 2004; Melander & Jørgensen, 2004; Melander *et al.*, 2004; Kristensen *et al.*, 2005; Hansson & Svensson, 2007; Elsgaard, 2010; Elsgaard *et al.*, 2010; Melander & Kristensen, 2011; Peruzzi *et al.*, 2012a) and implemented by a small number of farmers / growers in Scandinavia.

The technique is described under a range of names, including 'band steaming' 'intra-row steaming' 'steaming in narrow bands / strips' 'thermal band heating' and variations thereof. None of these are considered to be an accurate name / description, and it is suggested that the term "intrarow soil thermal weeding" (ISTW) most precisely describes the technique.

ISTW combines a number of well understood phenomena and techniques into a novel technique.

- All life forms, including weed seeds, have an upper temperature × treatment duration limit, above which death is certain.
- The use of steam (heat) for soil pasteurisation / management of soil-bourn pests, diseases and weeds has been used as far back as 1888 and extensively used until the 1960s when it was superseded by chemical fumigants (Gay *et al.*, 2010b).
- Soil steaming not only kills growing weeds it also destroys the weed seedbank thus preventing weeds from emerging in the first place, which also means no weeds can emerge from treated soil until new seeds are introduced from external sources, e.g., soil mixing or weed seed rain.
- However, 'traditional' whole-of-soil, multi-hour, high temperature steaming is not required to achieve seed or pathogen death, and that short duration, e.g., 3 minutes, steaming at lower temperatures e.g., 60°C is sufficient to kill weed seeds (van Loenen *et al.*, 2003).
- There is a direct physical relationship between the size of a seed and the depth from which that seed can emerge from, with the maximum emergence depth for most therophyte weeds in agricultural systems being about 5 cm (Roberts, 1982).
- Therefore focusing short duration thermal treatment on the intrarow to the maximum emergence depth of therophyte weeds can result in the complete elimination of the emergable intrarow seedbank.
- As thermal treatment is also lethal to crop plants / seeds, treatment must be undertaken before crop establishment. However, as the direct lethal effects of thermal treatment are short-lived, typically a few minutes to a few hours, crops can be established very quickly after treatment. More importantly as the crop is planted after treatment, ISTW can be used for any row crop, i.e., the issue of matching selective herbicide to weed and crop does not exist.
- As the effectiveness of the technique is fully determined at the time of application, if correctly implemented, ISTW would have exceptional levels of reliability, i.e., practically 100%, unlike, for

example, some residual herbicides that require the correct soil moisture, where to much or too little moisture reduces their efficacy, or selective herbicides where incorrect dose or adjuvants can result in incomplete weed control or crop harm.

ISTW is therefore considered to be unique among both chemical and non-chemical weed management techniques in achieving 100% control of all therophyte weeds, in all annual and biennial row crops for the whole duration of the crop with very high levels of reliability

## 3.2. ISTW research progression

The initial, exploratory work, into ISTW was conducted in the laboratory by injecting steam down small pipes into a channel filled with soil which represented the interrow (Melander *et al.*, 2002b; Melander *et al.*, 2002a; Jørgensen *et al.*, 2004; Melander & Jørgensen, 2004). This work focused on the amount of steam (energy) required, how the soil heated and cooled, and the effect of temperature and treatment duration on seedling emergence of a range of plant /weed species.

Having demonstrated the viability of the technique in the laboratory, research expanded into creating field 'band steaming' equipment to validate the laboratory research in the field both in terms of its effects on weeds and the agronomic benefits such as reduced hand weeding costs (Hansson & Svensson, 2004; Melander *et al.*, 2004; Kristensen *et al.*, 2005; Hansson & Svensson, 2007).

Other research investigated the impacts of soil conditions, such as texture, structure and moisture content on the efficacy of the approach (Jørgensen *et al.*, 2004; Melander *et al.*, 2004; Kristensen *et al.*, 2005; Melander & Kristensen, 2011). The ability to sow crop seeds directly after steaming, to investigate if the two operations could be combined into a single operation (Melander *et al.*, 2004). Side effects, both positive, e.g., increased nitrogen availability and negative e.g., reduced soil microbial populations and diversity due to steaming have been studied (Melander *et al.*, 2004; Elsgaard, 2010; Elsgaard *et al.*, 2010). Most recently a research group that had been researching the use of exothermic compounds to improve the effectiveness of 'whole-soil' mobile steaming technologies combined tested their steam + exothermic compounds idea for band steaming (Peruzzi *et al.*, 2012a).

# 4. Fundamental issues and misunderstandings in thermal weeding

To understand thermal weeding in general and ISTW in particular an understanding of the basic principles of thermodynamics is required. Unfortunately, this has been an area of misunderstanding within thermal weeding research, and therefore needs clarification. This misunderstanding, is a symptom of a deeper issue within the disparate sciences of physics and biology that underpin ISTW. Understanding the issues surrounding these quite different sciences is vital to understand the specific misunderstandings in ISTW.

## 4.1. Physics & biology

ISTW is unusual in that it uses a thermodynamic, i.e., physical, approach to achieve a biological objective. The sciences of physics and especially thermodynamics are much further along their phylogeny (development) than biology.

The sciences of thermodynamics originates in the industrial revolution and the invention of the steam engine, and has now achieved the highest level of phylogeny (stage 4) that of 'control' "where modelling and predictive equations lead to knowledge of useful substance amounts, design of systems, and applications to achieve desired ends" (Johnson, 2006) i.e., the science has a full mathematical description of processes and can use them to design and control new systems, i.e., engineering. Thermodynamics 'parent' science, physics, is also at stage four. Thermodynamics in particular, is the most secure scientific knowledge we have, as illustrated by Arthur Eddington's comment in 1915 "If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations—then so much the worse for Maxwell's equations. If it is found to be contradicted by observation—well these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation" (Eddington, 1928).

In considerable contrast, biology is mostly at stage 2, the descriptive phase where "where cause and effect relationships are established. The result of this phase is that the observed phenomenon no longer remains random, but can be expected whenever a series of foretold events happens. The phenomenon is still not able to be brought about at will, but its appearance is at least expected" (Johnson, 2006).

The combination of thermodynamics and biology is therefore not only an unusual, but also a rather unbalanced, scientific hybrid due to the different phylogenetic stages. The physics side can (in 'theory') be modelled and predicted down to the last joule. The biological side is often limited to establishing cause and effect through empirical tests, rather than being able to control events, even when there is a sound theoretical underpinning. This is often due to the inherent fuzziness / randomness / nonlinearity in biological systems. Considerable care is therefore required to ensure that the two different sciences are handled in the correct way and their techniques correctly applied to the appropriate parts of the system. For example, in physics theoretical calculations are more precise than many experiments so if theory and experiment diverge, then it is likely that the experimental methods are at fault. In biology, accurate predictive calculations are rare, and if theory and experiment vary, then it is most likely that theory is incorrect.

Thermodynamics, engineering and biology therefore tend to require rather different 'minds' and attract different personalities (Johnson, 2006) so it is considered vital to involve both biologists engineers / physicists to ensure both sides are rigorously addressed. As ISTW also involves manipulating and heating soil, perhaps one of the most complex and variable 'substances' on the planet, it is also considered important to involve soil scientists, ideally soil physicists, in research.

## 4.2. Temperature, energy and power

The relationship between temperature and energy and power is often an area of confusion, particularly in thermal weeding.

The 'base' entity is this relationship is energy, which is defined as 'the ability to do work' and is measured in joules (J).

When work is done (i.e., energy is 'used') it is done over time, i.e., it is a 'rate'. The relationship between joules and time is measured in watts (W), which is one joule per second, i.e. watts measures the **rate** at which energy is used.

The watt is unusual in the International System of Units (SI) in that it is not a fundamental unit but a compound one i.e. joules per second. In comparison there is no compound unit for speed, only the fundamental unit for distance multiplied by time i.e. meters per second. Therefore, terms such as watt-hour and kilowatt hour, are often misused as they mean joules per second per second, which means the **change** in power over time. This confusion is due in part to the term watt lacking the implicit inclusion of a time term, as in kilometres per hour.

Temperature is a measure of the thermal energy of an object, in common terms, how hot or cold it is, and is measured with the Celsius (°C) and kelvin (°K) scales.

The relationship between energy and temperature depends on the 'heat capacity' which is the amount of energy required to change a materials temperature by a given amount and is measured in joules per kelvin. Heat capacity is an **extensive** property, i.e. it scales with the size of a physical system. This is less helpful in engineering where an **intensive** property which is independent of the size of a sample is more convenient. The intensive form of heat capacity is 'specific heat capacity' (or just specific heat). Specific heat is the amount of energy (J) required to raise the temperature (K) of a given mass (grams) of a material i.e. joules per kelvin per gram.

Therefore a hot material with a low specific heat can contain less thermal energy (J) than a cooler material with a high specific heat, for example hot air contains less thermal energy than steam at the same temperature mass for mass. Somewhat counterintuitively this means that the cooler steam can heat the target material, e.g., a weed, to a higher temperature than the hotter air. Unfortunately temperature has sometimes been used as an unintentional proxy for energy in the thermal weeding literature, which is incorrect. This has particularly been the case when comparing the effectiveness of different thermal weeding machines. However, temperature alone, i.e., without knowledge of the heat capacity and mass of energy transfer media in the different weeders, and their efficiency / effectiveness, can not determined why one machine performs better than another. This is why no clear correlation between temperature and weeding effectiveness has been found as it can not exist.

In parallel with confusion over 'temperature', the term 'heat', is used in ordinary language as a synonym for both energy and temperature. As energy and temperature are quite different properties the use of the term heat in this review will restricted to its technical meaning, i.e. the transfer of thermal energy from one system to another.

# 5. ISTW technical analysis and research

There are considered to be two fundamental technical factors underpinning ISTW

- Optimising the temperature × treatment duration × soil moisture × soil structure variables to maximise both seed death and energy efficiency, i.e., optimising treatment conditions;
- Transferring sufficient energy from fuel to soil to achieve seed death, while maximising overall energy efficiency, i.e., optimising machine design.

## 5.1. Treatment temperature × duration

The use of heat to both kill and treat a wide range of biological organisms is well established science and technology, for example, autoclaving. The subsection applying to seeds is reasonably well understood, for example, heat was widely used to treat seeds, e.g., hot water baths, to manage seed borne fungal pathogens before the introduction of agrichemical seed treatments. With the rise of chemical approaches interest in thermal approaches dwindled so research over the last 50 years has been limited. However, there has been a resurgence in interest recent years with the increase in organic agriculture and also loss of chemical treatments. It is now once again being used commercially for seed disinfestation and in the case of ISTW for weed management. Therefore there is both sound theory and empirical evidence underpinning the use of heat to treat and kill seeds.

### 5.1.1. The impact of the five temperature 'zones' on treatment × duration

The relationship between temperature and the duration of treatment on living things can be both critical or unimportant depending on the situation. The effect of temperature on organisms can be divided into five 'zones'. The specific temperatures of each zone varies considerably among species, e.g., tropical vs. arctic species and what is being treated, e.g., an animal vs a plant, vs. a seed vs a bacterial spore, so the temperature figures below are a general guide, rather than absolute.

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).

In terms of thermal weeding, including ISTW both cold and hot temperatures could be used. Indeed, the use of lethal cold temperatures in the form of both dry ice (solid carbon dioxide) and liquid nitrogen have both be tested for foliar thermal weeding (Fergedal, 1993), however they were found to be ineffective due to inherent (i.e., due to the laws of physics) very poor energy efficiency and practical issues (see also page 30). If such approaches are not viable for foliar thermal weeding it is considered very unlikely they would be practical for ISTW. Only heat is therefore considered viable.

Semi-hot temperatures are of more interest for activities such as seed treatments, where the temperature x duration combination needs to be lethal to the pathogen but safe for the seeds. This is the temperature range (along with the semi-cold range) where the duration of treatment can be as, or even more, critical for achieving the objectives than the temperature. In this regard temperature and treatment duration are interchangeable, i.e. a lower temperature, say 45°C with a longer duration say 60 seconds can have the same effect as a higher temperature, say 55°C for a shorter duration say 30 seconds. The temperature × duration interaction is akin to the effect of thermal time (aka heat units) on plant growth.

In the lethal temperature zones seed death is very rapid, e.g., < 5 seconds. This is also about the minimum duration which it is practical to apply heat to seeds or material containing seeds, such as soil, and then remove it again, for example placing seeds in a hot water bath, removing them, and then placing in a cold water bath to cool them.

It is the lethal hot temperature zone that is considered of primary interest / importance for ISTW due to the need to:

- ensure 100% seed death, therefore the temperature needs to be sufficiently high to provide a good margin of error;
- the need to undertake heating as quickly as practical, due to the desire to maximise work rates.

### 5.1.2. Research findings

Research studying minimum temperatures and durations required for effective soil steaming showed that short duration, e.g., 3 minutes, steaming at lower temperatures e.g., 60°C was sufficient to kill weed seeds and that the long duration steaming, i.e., several hours, that was typical of that used by industry for whole-soil steam pasteurisation was not required (van Loenen *et al.*, 2003). The initial laboratory work studying ISTW showed that seedling emergence started to decline around 40-50°C and that emergence ceased between 80-90°C depending on species Figure 1 (Melander *et al.*, 2002b; Melander & Jørgensen, 2004), although the authors report lower figures of 70° as they were focused on 90-99% reduction in emergence, not 100%.

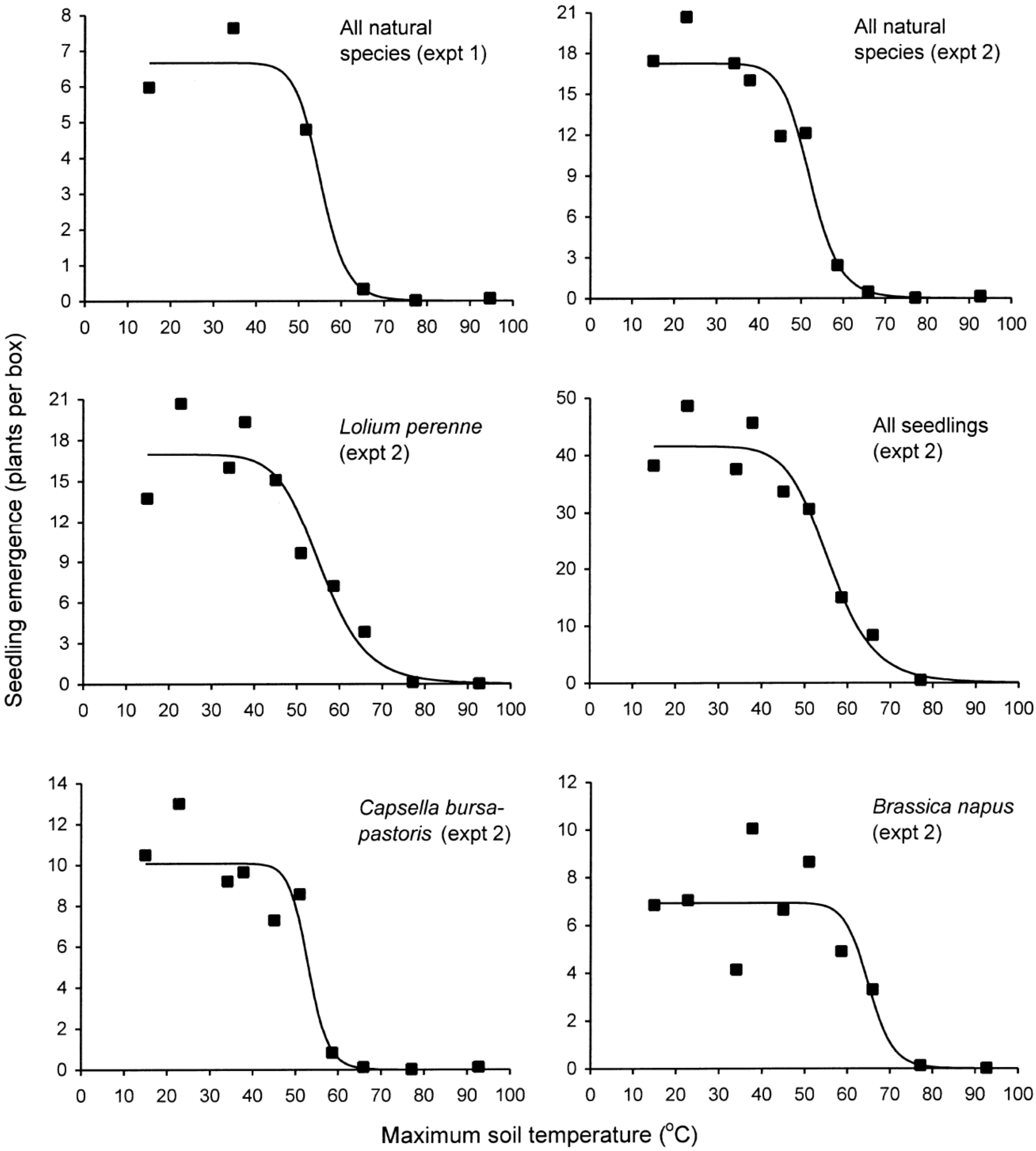



Figure 1. Sigmoid relationship between maximum soil temperature and seeding emergence. Reprinted from Melander & Jørgensen (2004).

Melander & Jørgensen (2004) also looked at the effect of duration, via removal and cooling of the soil at time intervals of 0, 300 or 1,200 seconds, but the effect was small so the results were not reported separately. In further studies Melander & Kristensen (2011) confirmed the lethal temperature was 80-90°C depending on plant species, and soil texture. The third experiment in the paper found that the effect of duration was even less significant

## 5.2. Moisture

Moisture, i.e. the water content, of the target, i.e. seeds, soil and other media that are to be heated (or cooled) and the heat transfer media, e.g., hot air vs. steam, often has a critical impact on the outcomes.

### 5.2.1. Biological

The moisture level of biological materials can have a dramatic impact on their response to heat. In general dry heat or a low moisture content of the target means that heat has (much) less of an effect than when wet / moist heat or the target has a high moisture content (Merfield, 2006). For example dry seeds placed in an oven can withstand higher temperatures for much longer than imbibed seeds placed in hot water. This effect is most pronounced when the temperatures are in the 'semi hot' temperature zone with the effect reducing as temperatures reach the 'lethal hot' zone.

### 5.2.2. Physical

The issues relating to the effect of water on energy transfer and heating is covered in detail on page 29.

Briefly, and in regard only to the water content of the target, the presence of water within the target to be heated means that more energy is required to reach the target temperature. In addition, because of the high specific heat and latent heat of evaporation of water, compared with other materials, e.g., soil, the presence of water can have a disproportionally greater impact on the amount of energy required. In addition if the target temperature needs to be higher than 100°C, i.e., the boiling point of water, the latent heat of evaporation of water places a large energy 'hurdle' to overcome.

### 5.2.3. Research findings

There are only three papers found studying the effect of soil moisture in ISTW Melander & Kristensen (2011) Kristensen et al., (2005) and Jørgensen et al., (2004) with the latter two papers being reports of different aspects of the same experiments.

Melander & Kristensen (2011) used two soil moisture levels in two soil textures: a sandy loam at 5.3% and 15.3% SMC; and a sand at 3.7% and 12.8% SMC (percentages by weight). The dryer soils were quicker to heat up than the moister soils with a clear difference on the effect of moisture between the two soil textures (Table 1).

Table 1. Percentage increase in time taken to reach target temperatures of a moist compared with dry soil for two soil textures. Calculated from (Melander & Kristensen, 2011).

| | Temperature | | | |
|---|---|---|---|---|
| Soil type | 60°C | 70°C | 80°C | Mean |
| Sandy loam | 4% | 9% | 2% | 5% |
| Sand | 31% | 25% | 16% | 24% |

The results of the effect of moisture on seedling emergence, were less clear cut, with only total seed emergence being statistically lower (P 0.05) for the dry sandy loam (Melander & Kristensen, 2011).

Kristensen *et al.*, (2005) and Jørgensen et al., (2004) calorimetrically (experimentally) determined the specific heat for a dry sand and clay soil (sand = 0.858 and clay 0.896·kJ·kg·°K) and then calculated the specific heat for the two soil types at quantitatively determined 'dry' and 'normal' states (Table 2).

Table 2. Specific heat of two soil textures at normal and moist water contents, abridged from (Jørgensen *et al.*, 2004)

| Soil type | Moisture % | Specific heat Mj·kg·°K | Efficiency % |
|---|---|---|---|
| Normal sand | 8.7 | 1.124 | 92 |
| Dry sand | 5.6 | 1.035 | 95 |
| Normal clay | 10.0 | 1.195 | 91 |
| Dry clay | 8.8 | 1.162 | 100 |

However, Jørgensen et al., were comparing the efficiency rather than how long it took the soil to reach the target temperature, but the specific heat values are sufficiently different that they should have a significant effect on the time taken for the different soils to reach the target temperature. They did not present any data comparing seeding emergence from moist vs. dry soils.

Therefore with the limited research there is insufficient empirical data to rigorously compare with thermodynamic theory, but the results of the effect of water on rate of heating are generally consistent with theory.

In regard to the effects of moisture on seedling emergence, it is not clear from the methods of Melander & Jørgensen (2004) how long the soils, and thus the seeds in them were left for moisture levels to equilibrate and therefore how well imbibed the seeds were, even though it was stated that having imbibed seeds was the aim. The total number of emerged seedlings and use of only three plant species (all surrogate weeds) mean that these results are not yet sufficient to draw firm conclusions.

### 5.2.4. Further research

As the general effects of seed moisture on seeds susceptibility to heat is understood and seed moisture can be manipulated in the field via soil moisture through the use of irrigation, the specific effects of moisture on seed mortality at temperatures in the 80 to 90°C range, i.e., if it has a biologically significant impact on the percentage of seed mortality, and/or if seed moisture has an significant impact on the duration of heating, are considered a critical issue for further research.

## 5.3. Soil texture, structure and moisture

From a thermodynamic perspective, soil texture (the proportion of sand, silt and clay) and soil structure (how soil particles are aggregated) will have an impact, potentially significant, on the heating dynamics of soil and the effects on seed mortality. To understand the impacts of texture it is first necessary to consider how heat is transferred to soil.

### 5.3.1. Forced convection to conduction

In thermal weeding, including ISTW, thermal energy is initially transferred from the source to the target, by 'forced convection' i.e. the hot air or steam is 'blown' through the machine from the combustion point, until it contacts the target (soil particle or a weed plant) at which point the energy is transferred by conduction through plant tissues, soil aggregates, particles and weed seeds. The key difference between these two mechanisms for thermal weeding is the rate of energy transfer over distance. Forced convection can transfer thermal energy very quickly, e.g., $5 \cdot m \cdot s^{-1}$, i.e. at the speed of the gas stream, while transfer by conduction is much slower, often an order of magnitude slower or more e.g., 2 to 7 $W \cdot m^{-1} \cdot K^{-1}$. Therefore to maximise the rate of energy transfer, the greatest use must be made of forced convection and the amount of conduction minimised.

For clarification, steam also carries the heat to the target by forced convection, when it contacts the target (assuming the target at a sufficiently cool temperature for steam to be able to condense) then condensation assists with the very rapid transfer of heat from the steam stream to the **outside** / **surface** of the target, from where it can only move via conduction inside the target, i.e., once the heat has been transferred to the target's surface there is no difference between steam and hot air as the mode of heat transfer within the target is **exactly** the same.

In practice this means that the target should be as small as possible, e.g. soil structure should be reduced to individual soil particles and weed seeds, i.e. soil structure is destroyed. However, destroying soil structure is highly undesirable for a multitude of agronomic reasons, so a balance needs to be struck between reducing soil aggregate size to minimise the amount of conductive heat transfer and maximising soil aggregation for its many other benefits. To optimise that balance a number of factors need to be understood.

## 5.3.2. Soil texture

Soil texture can effect the rate of transfer for a number of reasons.

Soils are made of individual particles that vary very considerably in their sizes: sand particles are 0.05-1.00 mm in diameter, silt is between 0.002 and 0.05 mm and clay <0.002 mm. Heat will take therefore longer to reach the centre of the larger sand particles than silts and clays due to their different size, though the size of this effect is small due to the overall small size of the particles, despite the considerable comparative difference in size. However, except in soils without any soil structure / aggregation i.e., sands, the impact of individual soil particle size is almost completely overridden by soil aggregation (see below).

The different soil textures also have difference particle densities, though the variation is relatively small, e.g., sand = $2.655 \cdot g \cdot cm^3$ and clay $2.837 \cdot g \cdot cm^3$, so there should be small differences in the amount of energy required to heat different soil textures due to varying particle densities. However, particle density is to a large degree overridden by soil bulk density, which is also largely determined by soil texture. The effect of texture on bulk density is the opposite to particle density with sands having the highest bulk density e.g., sandy soil $1.6\ g \cdot cm^3$, loam $1.4\ g \cdot cm^3$, silt loam $1.3\ g \cdot cm^3$, clay $1.1\ g \cdot cm^3$.

Soil texture is also a primary determinant of soil structure, which can have an even greater impact on the energy required to heat soil.

## 5.3.3. Soil structure / aggregates

The interaction of soil structure, particularly how soil aggregates, on heat transfer, especially when mechanical mixing is used (as is the case in some forms of ISTW), is very complex.

Soil aggregates, from the perspective of heat transfer, are effectively large 'soil particles' in that the edge of an aggregate is where forced convection changes to conduction, and therefore the speed of heat transfer into the soil dramatically declines. Soil aggregates can be less than a millimetre, to centimetres across, depending on a considerable number of factors, including, texture, compaction, soil organic matter and moisture. The larger the size of aggregates the larger the proportion of the soil that can only be heated by conduction, and therefore that proportion of soil may not reach lethal temperatures. As weed seeds are distributed throughout the soil, some seeds will reside within soil aggregates, and therefore may not receive a lethal thermal dose, and therefore survive. The size of soil aggregates is therefore considered a key parameter of the effectiveness of fully heating the soil to lethal temperatures and therefore killing all weed seeds. Soil aggregate size is also a parameter that can be manipulated, i.e., through tillage, so can be controlled to some extent.

## 5.3.4. Soil moisture and structure

Moisture plays an additional role to the issues of specific heat (discussed on page 19), in that soil moisture content has a key role in determining the plasticity of soil, especially for silts and clays, i.e., dry soils are highly resistant to destruction of structure / aggregates while wet soils can loose their structure very easily. Moisture can therefore have an important impact on the ability to optimise aggregate size for heat transfer.

## 5.3.5. Soil texture and soil moisture

In addition, the different soil texture classes have different soil water holding capacities with sand the lowest (620 mm per 30 cm soil depth ), and clays the highest (3,040 mm per 30 soil depth). A moist sand and a moist clay can hold a significantly different mass of water and therefore will require different amounts of energy to heat that water up.

### 5.3.6. Compaction in silt and especially clay soils compared with sands

Soil moisture also plays a critical role in soil compaction and the creation of large dense aggregates i.e., 'clods', which can have dramatic negative effects on crop performance. To date most of the research on ISTW has occurred in Denmark and Sweden, which are dominated by sandy soils which are inherently structureless, i.e., they do not form clods. Clay and silt soils, which are often the most fertile and therefore sort after for cropping, are highly susceptible to compaction / forming dense clods. Traditional soil steaming results in high SMC, often at field capacity, and, if such soils are then subjected to tillage and/or compaction while in a moist state, and potentially, especially when still hot, severe compaction could result with commensurate negative crop impacts. It therefore needs to be determined if the shorter duration steaming used in ISTW significantly increases SMC and also if ISTW at higher SMC results in compaction of silt and clay soil textures, especially when mechanical mixing is used.

### 5.3.7. Soil organic matter

A final complicating factor affecting heating of soil is the organic matter content. Soil organic matter (SOM) has its own thermodynamic properties, e.g., having a low specific heat and poor conductor, but more critical is the way it modifies the properties of the rest of the soil most important of those is the impact on soil structure / aggregation and water holding capacity with increasing SOM content improving structure and increasing water holding capacity.

### 5.3.8. Research findings

Three papers study the effect of soil texture and structure in ISTW (Jørgensen *et al.*, 2004; Kristensen *et al.*, 2005; Melander & Kristensen, 2011), though as noted on page 19 the Jørgensen et al., and Kristensen et al., papers report the same data.

Melander & Kristensen, (2011) found the sand took on average 7% longer to heat up than a sandy loam across all target temperatures, which is consistent with sands having a higher density. However, this average figure includes dry and moist soils, which as reported on page 19 moisture had a greater effect on the rate of heating of the sandy soil than sandy loam, contrary to what was expected due to sand having a lower water holding capacity. However, the interpretation of the interaction with soil texture is hampered by lack of detail in the paper, e.g., mass of the two soils as the experiments were conducted on a volume of soil, which are vital for a full understanding, so drawing conclusions from this result is not possible.

The effect of aggregate size, which were designed to represent coarse and fine seedbeds (which are fully described in the original paper and which used the sandy loam soil) found that the coarse soil heated up faster on an overall average of 9% (Melander & Kristensen, 2011). The effect on seedling emergence was an 18% increase in weed emergence overall from the coarse soil, though with differences among species, and with the total numbers being low, the difference was not statistically significant.

As noted on page 19 and Table 2, Kristensen *et al.*, (2005) and Jørgensen et al., (2004) experimentally determined the specific heat capacity for the two soils. However, as they were focused on determining efficiency they did not report how long the different soils took to reach target temperatures.

No research has been found studying the effects of SOM on soil heating.

### 5.3.9. Controllable vs. uncontrollable environmental conditions

The above thermodynamic analysis and experimental results clearly show that there are many factors that influence soil heating, some of them conflicting, and some only partly understood, both theoretically and empirically. This means that a detailed theoretical modelling of how any one soil will absorb heat is very complicated and is probably beyond current modelling abilities. This is an example of where the stage 4 phylogeny of physics runs into the stage 2 phylogeny of biology.

In addition, due to the many interacting and competing soil factors, it is considered impossible to give a 'standard' treatment (i.e., energy input × work rate) that covers all soil conditions as the number of soil conditions requiring different treatment parameters, is vast. In addition, soils can be highly variable over small distances, e.g., meters, with individual fields having multiple soils textures with widely varying moisture levels. Therefore even if a 'table' of treatment settings could be created for the full range of soil conditions, this would be of no use where soil conditions vary across individual fields. It is therefore proposed that a control / feedback system is required for ISTW machinery, to ensure that the machinery can automatically compensate for varying soil conditions such as texture, structure and moisture. All of the factors that affect the ISTW process and therefore impact seed mortality should, therefore, be divided into two types:

- those that can be 'controlled' (manipulated / altered / managed), at least to some extent, i.e., soil / seed moisture levels, soil aggregate size;
- those that can not be controlled, i.e., soil texture, soil organic matter.

It is noted that some conditions, e.g., soil moisture, are partly under human control (irrigation), and partly outside human control (rain). However, for those conditions that can be manipulated to some extent, they should be altered, as far as practical, so they are optimised to maximise seed death and minimise energy use, e.g., irrigating to increase moisture, tilling to decrease aggregate size. For those conditions that can not be, or only partly manipulated, the ISTW treatment process has to be able to adapt to ensure that optimum conditions for seed death are met, i.e., there needs to be a control system that ensures that the different heating requirements of different soil textures and moisture levels are automatically compensated for, i.e., the maximum soil temperature is constantly monitored and the application process adjusted (increased energy flow or decreased work rate) to ensure a consistent result.

The alternative to compensate for this variability is to 'over-engineer' the system, i.e., determine the maximum energy required to heat the soil which requires the most energy to heat and then use that on all soils. However, this will increase fuel consumption, which is the opposite of what is desired, and, if soils are heated above 100°C, this may cause much more harmful effects than at lower temperatures which may have unforeseen negative outcomes. Therefore automatically controlling the temperature of treated soil is considered preferable.

The only variable not covered by this control system is the effect of soil aggregates 'protecting' seeds due to the slow rate of heat conduction into the aggregates. This is discussed on page 23.

### 5.3.10. Future research

Drawing generalisable conclusions from the above literature on soil texture, structure and moisture is not possible, and clearly further research is required. However if the arguments above, on the need for a treatment control system is correct, further research on the effect of texture and SOM on heating requirements is considered low priority as this will automatically be compensated for by the control systems.

Of the remaining parameters, aggregate size and soil moisture are considered the key issues requiring further research.

#### 5.3.10.1. Aggregate size

Research is required to determine the effect of aggregate size, potentially for different soil textures, on seed mortality at treatment temperatures and durations that are practical from an agronomic perspective. This will provide farmers with a guide to how fine a tilth is required.

### 5.3.10.2. Soil moisture

Soil moisture has conflicting outcomes:

- The more water in the soil the more energy is required to heat it up, so soil moisture needs to be minimised to minimise energy use.
- However, imbibed seeds are more susceptible to heat treatment, especially in the 'semi hot' temperature zones, so this indicates that soils need to be moist to wet, probably for at least 24 to 48 hours prior to treatment to ensure seeds are fully imbibed.
- However, the effect of water on seeds in the lethal temperature zone, e.g., above 90°, may be lower, or inconsequential, in which case soil moisture may be irrelevant for effective seed death.
- But, soil moisture has a critical effect in clay and silt soils on the ability to reduce aggregate size, which depending on the importance of soil aggregates for protecting seeds from heat is, may or may not be a critical factor.
- Soil moisture can have a considerable effect on heat transfer within soils, but, most of the research has been focused on natural warming of soils in-situ, not artificial heating.
- If increased soil moisture causes soils to severely compact during treatment, especially when mechanical mixing is used, then soil moisture will need to be low for treatment of compaction susceptible soils.

Therefore research is required into the effect of soil, and therefore seed, moisture on seed mortality in the 80 to 90°C temperature zone, with there possibly being some value in extending the temperature range up to 100°C.

If moist soils make seeds significantly more susceptible to heat at these higher temperatures, then there is a trade-off between needing more energy to heat moist soils (due to the water content) but needing to heat them less because weed seeds are more susceptible to heating when moist; vs. needing less energy to heat dry soils but needing to heat them more because the weed seeds are less susceptible to heating when dry. If moist seeds are more susceptible at 80-100°C then the above trade-off needs both theoretical and empirical research. The effect of moisture on heat transfer further complicates matters, and again it requires empirical research.

## 5.4. Mechanical soil mixing

Mechanical mixing / agitation of soil during heating has multiple effects that need to be considered:

- mixing helps ensure that all of the soil is heated up to the same temperature, regardless of location within the treated band;
- mixing can be used to reduce aggregate size;
- however, mixing increases engineering complexity and may cause significant soil compaction, especially in silt and clay soils.

Two approaches have been taken in previous ISTW / band steaming work: (1) direct steam injection into the soil and (2) mechanical mixing of steam and soil.

In all laboratory work and the field prototype used by Melander et al., (2002b) and the field steaming equipment used by Hansson & Svensson (2004; 2007) working in Sweden (Swedish design) steam was injected directly into the soil. In the laboratory and field prototype this was using a vertical tubes while the Swedish design used a horizontal trident shaped outlet (Figure 2).

The machines used by Melander & Kristensen, (2011) and their colleagues in Denmark (Danish design) uses an inverted U shaped tunnel with a series (normally four) of horizontal axis rotors with tines (similar to a rotovator) to mix the soil with the steam which applied at the front of the hood (Figure 3).


Figure 2. Swedish band steamer using steam injection without mechanical mixing using 600 kw steam boiler water tanks and associated equipment. Photo credits: Bo Melander.

Figure 3. Danish design band steamer: left, prototype band steamer using horizontal axis rotating tines reprinted from (Kristensen *et al.*, 2005); right, field scale version of prototype band steamer with 900 kw pressurised steam boiler, three phase generator and water tank.

## 5.4.1. Soil mixing and heat transfer

Ensuring even heating of soil is considered vital for to achieve 100% seed mortality because the temperature × durations used are only just sufficient too achieve seed death, i.e., there is a limited margin of error / over-engineering of the system. The small soil volumes heated over short periods of time in ISTW poses particular problems compared with whole-of-soil steaming lasting hours, as there is not enough time for unevenly heated patches of soil to equilibrate, plus there can be significant edge cooling. Mixing the soil with the hot air or steam is therefore a means of:

- Maximising heat transfer via forced convection and thereby minimising transfer by conduction as discussed on page 20.
- Making sure all of the soil is evenly heated.
- It may help to improve efficiency as all of the soil is heated to the target temperature but not beyond as opposed to needing to overheat those parts of the soil next to the gas (e.g., steam) outlets so that the heat can be conducted to those parts of the soil further away from the outlets.
- Depending on how mixing is achieved, it could also decrease the size of soil aggregates (create a finer tilth) thereby also reducing the amount of heat transfer by conduction required.
- Mixing may help to increase the rate (i.e. speed) of heating, which would be beneficial for maximising the speed of field operations.

Once mixing stops and treated soil is back in contact with the bulk of the soil, edge cooling will commence, however, this is not considered a significant problem as long as the soil has received the necessary temperature × duration treatment while in the machine.

### 5.4.2. Additional mechanical complexity

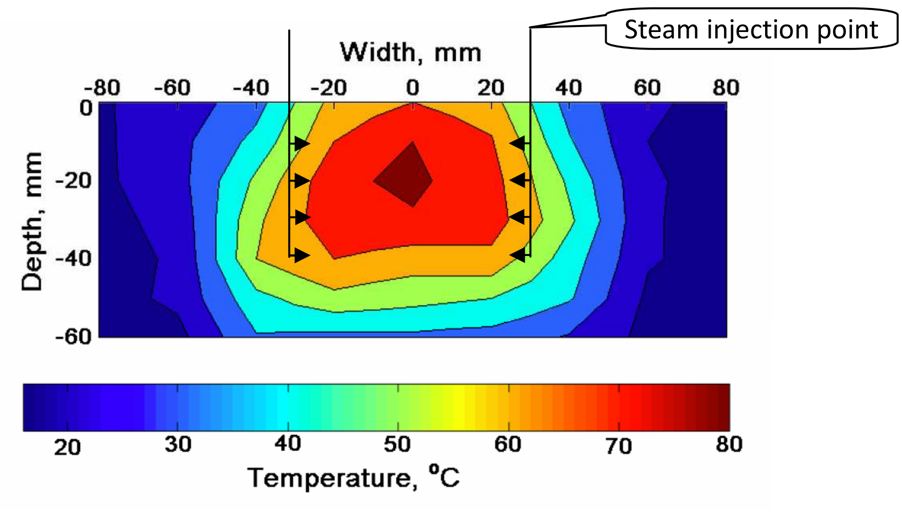
However, mixing soil creates a considerable amount of additional mechanical complexity, as seen by comparing Figure 2 and Figure 3. As the rotors in the Danish design are operating in the heated soil, there may also be issues of needing heat tolerant components, e.g., bearings.

### 5.4.3. Negative effects on soil aggregates / creating compacted soils

Mixing soil when it is hot, and especially when it is hot and wet, may well have a considerable effect on soil structure, i.e. it cause excessive destruction of soil aggregates. In clay and silt soils there is the potential that aggregates are so completely destroyed that soil structure is eliminated resulting in the treated soil becoming very compacted / hard and unsuitable for crop growth, as discussed on page 22.

### 5.4.4. Research findings

Initial laboratory band steaming research by Jørgensen et al., (2004) looked at the dissipation of heat from the treated band They used four vertical tines to inject the steam placed on the edge of the band, injecting the steam inwards into the band at depths of 10, 20, 30 and 40 mm under the soil surface with a band width of 60 mm Figure 4.




Soil temperatures from a cross-section across the groove, measured 40 sec. after treatment. The width is measured from centre of the treated band. Treated area: With –30 - +30, depth 0 - 50 mm.

Figure 4. Soil temperature profile, reprinted from (Jørgensen *et al.*, 2004) with the location of the steam injection points added.

The resulting temperature profile (Figure 4) shows clear variation in the soil temperature both vertically and horizontally. Soil near the surface is cooler, presumably due to loss of heat from the soil surface while there is a clear edge effect due to the untreated soil bulk cooling the treated soil. This indicates that there are issues with direct heat (steam) injection achieving even heating, though this is only one, of many possible injection configurations that could be used.

A useful analogy is the work undertaken by Gay et al., (2010b) comparing standard steaming where the steam is forced under pressure into the soil from the surface down by the use of sheets or metal containers (‘top-down’), with the system they developed for introducing the steam into the soil via vertical pipes (‘bottom-up’). They clearly showed the condensation front in the soil was blocking the passage of steam in a top-down approach, which their bottom-up approach avoided. The resulting soil heating profiles clearly demonstrating a large improvement in effectiveness of the bottom up over the top-down approach. They also note that bottom-up application of steam is not a new idea, e.g., steam ploughs and similar devices were developed in the 1950s.

Another comparison is the work by Peruzzi et al. (2012b) comparing different steam injection systems for their exothermic compound technique, which again showed clear differences between steam injection depths on emerged weeds vs. the weed seed bank, with surface steaming having a larger effect on emerged weeds and deeper steaming on the weed seed bank.

All this work indicates that the method of injecting and/or mixing hot gasses with soil has significant impacts on the efficiency, effectiveness and outcomes of heating.

No research has been found studying the effects of mixing on heat transfer and impacts on soil structure specifically for ISTW. Informatively, the original developers of ISTW (B. Melander, T. Heisel, M. H. Jørgensen, L. Elsgaard, E. F. Kristensen and J. K. Kristensen), started with a steam injection system in the laboratory, but then designed a field applicator that included four mixing rotors, however, the reasons for this change of approach was not published, but the rationale was that the injection tines did not heat up soil clods and rotors gave a better and more homogenous seedbed (Erik Kristensen, pers. comm.).

It has been noted that even with current field machines 100% seed mortality is not being achieved (Melander & Kristensen, 2011) though the reasons given for this and the research undertaken focused on the effects of soil texture, structure (aggregates providing refugia for seeds) and moisture (which have been discussed in detail in previous sections). It is therefore clear that there are still issues with the effectiveness of current field machines that need addressing by further research.

All of the published research into band steaming that use mechanical mixing have been completed in Denmark and Sweden, predominately on sand or sandy soils, which are common in those regions, and which do not form strong aggregates or become highly compacted if compressed when in a plastic state. It is not considered a safe assumption that because band steaming is working in these countries that it can be used in other locals with clay and silt based soils.

### 5.4.5. Future research

It is therefore clear that ensuring even soil heating is still an issue and requires further research. There are likely to be differences between hot air and steam on the evenness of heating due to their different heat capacities and therefore volumes and temperatures. Moisture content of the soil may also play a role on the evenness of heating.

However, it is considered more important to initially investigate the potential for a combination of mixing and heating causing compaction, especially when using steam and/or on moist / wet soils and particularly silt and clay soils. Until this is confirmed or refuted as an issue, other research into mixing soil during heating is considered to be premature.

## 5.5. The use of exothermic compounds

The most recent ISTW research has tested the potential for using exothermic compounds such as potassium hydroxide (KOH) and calcium oxide (CaO) in conjunction with steam to "increase the effect of steaming" (Bàrberi *et al.*, 2009) and use that approach for band steaming (Peruzzi *et al.*, 2012a). However, as discussed by Jørgensen et al., (2004), there is no overall improvement in the energy efficiency of the process as a whole (e.g., a full lifecycle analysis (Guinée, 2002)), rather there is a significant reduction in total energy efficiency due to the high energy costs and energy losses involved in producing KOH and CaO, plus all the energy and other costs of the infrastructure required for their production and handling. In addition the large quantities of calcium or potassium that are added to the soil as part of the process (e.g., $4 \cdot \text{tonnes} \cdot \text{ha}^{-1}$ for whole of soil heating) which may be in excess of what is required for optimal soil nutrient levels, especially if the process is used on a regular basis. The use of exothermic compounds also increases the complexity of the machinery, especially as KOH and CaO are caustic / corrosive, thus requiring corrosion resistant materials violating the KISS principle. Finally the economics of the system also hinges on the relative cost of the exothermic compounds vs the fuel cost savings, which with the greater total energy use in the exothermic system, indicates that this will be more expensive on the economic assumption that all the energy used costs approximately the same. On this basis, the use of exothermic compounds is not considered a practically viable technology and research should focus on optimising the physical-thermal system.

## 5.6. The effect of ISTW on soil biology and chemistry

One of the concerns about soil steaming as a general technique is that it is indiscriminate in its effect as it kills both harmful organisms as well as beneficial ones and it can alter soil (bio)chemistry. The level of harm is such that whole soil steaming / thermal treatment is prohibited under organic agricultural standards.

Two papers have been published studying the effects of ISTW, in the form of band steaming, on soil biology and chemistry.

Elsgaard et al. (2010) found that the mechanical soil disturbance associated with band steaming had a negligible effect, and that it was the steam heating that was responsible for a reduction of fungi and increase in bacteria coupled with an overall reduction in soil microbiological activity. This effect persisted for the full measurement duration of 90 days. The level of the depression of activity and change in ecology were considered "tolerable", and it was noted that as the treated volume of soil is <10% of the plough layer, long term effects on the bulk of the soil should be minimal due to soil mixing from tillage and therefore the technique should be permissible in organic farming.

Elsgaard, (2010), also evaluated the effects of band steaming on mineral nitrogen and water soluble carbon dynamics. Ammonium concentrations increased significantly due to a decrease in nitrification due to nitrifying bacteria being killed, while water soluble carbon levels and nitrate levels were not significantly different. The increased ammonium levels were considered to be potentially agronomically beneficial in terms of increased plant growth, although for direct drilled crops, high nitrogen levels at germination are widely known to be potentially harmful, so this suggestion needs experimental verification.

These results are in agreement with research on soil steaming in general (Mulder, 1979), in that band steaming, even though it is of shorter duration and lower temperature than normal steaming practice, still changes soil biology and chemistry, in both positive and negative ways, which can persist for agronomically significant periods of time. However, due to the small volume of treated soil compared with the plough layer, the overall impacts on soil are likely to be minimal and other soil manipulations, such as tillage, can also have large effects (Brady & Weil, 2008) so the effect of ISTW on soil biology and chemistry needs to considered in context of the impacts of soil from all agricultural operations. Clearly this hypothesis needs to be validated over a range of soils when ISTW is used on a regular basis to determine if longer term effects are found.

### 5.6.1. Future research

Therefore, there is clearly a need for considerable research in this area, including:

- Determining if there are long term effects (negative and positive) on soil, particularly with regular use of ISTW and comparing that with other standard soil management practices, e.g. tillage, and also where ISTW could be used to reduce other harmful soil operations, e.g. be used for strip / zone tillage systems.

- Studying the direct effects of thermal treatment on crops (e.g. due to increased nitrogen) in the absence of weeds.
- Establishing if ISTW is useful for management of soil-borne pests and diseases, e.g., damping off and nematodes, i.e., ISTW could be as potentially a valuable replacement for agrichemicals for soil-borne pests and diseases management as it is for weed control.

# 6. General issues of Steam vs. flame for thermal weeding

There has been a widespread belief among many weed scientists interested in thermal weeding that steam is a ‘better’ heat transfer system than open flames (Bo Melander, Aarhus University, Denmark; Johan Ascard, Swedish University of Agricultural Sciences, Sweden, pers. comm., Merfield, 2006; Merfield *et al.*, 2009). Most of this has been focused on foliar thermal weeding, which is where only the aerial parts of plants are heated i.e., ‘classical’ flame weeding.

The origins of this belief that steam is better than flame are not clear. Probably one factor is that water has an unusually high specific heat (4.2 $kJ \cdot kg \cdot °C^{-1}$) and a very high latent heat of evaporation/condensation (2,260.0 $kJ \cdot kg^{-1}$) compared with dry air (1.0 $kJ \cdot kg \cdot °C^{-1}$) which means it has a high thermal energy density. This attribute is reflected in the common knowledge that steam and hot water produce more severe burns than open flames for a similar level of exposure.

Early research comparing steam and hot air also favoured steam. For example, Bertram, (1994) showed that steam/air mixtures were more **efficient** at transferring heat to an artificial plant leaf than was hot air alone. Similar arguments were put forward by Čėsna et al. (1998) and Sirvydas et al. (2002).

### 6.1.1. Efficiency vs. rate vs. better

The word ‘efficient’ when used in relation to heat transfer and physics in general has a specific meaning, that is quite different from the everyday concept of ‘better’. In physics, efficiency is the relationship between the output / outcome and the energy expended. However, in the work of Bertram, and in real world foliar thermal weeding, time, i.e. the duration of exposure of the weeds to the flame, is a critical, and often misunderstood, component of overall efficiency. A simple thought experiment can illustrate the critical role of time. Two identical, sealed and thermally isolated (well insulated) containers each hold an identical weed. Into one box a given amount of energy (joules) is introduced as steam and into the other as dry air, and the boxes are resealed, and left to equilibrate. The final temperature of both boxes must be the same, as it is only the amount of energy, not the energy transfer medium (steam vs. dry air), that influences the final temperature, i.e. the efficiency of steam and air are exactly the same. The key difference between this scenario and the work of Bertram and others, and real world thermal weeding, is that the effect of time has been excluded. The real difference between wet and dry heat as a means of energy transfer is the **rate** of transfer, i.e. steam, especially when latent heat of condensation is involved, is a much **quicker** means of transferring energy. In short **better** really means **faster**.

### 6.1.2. Effectiveness: Matching heat transfer media to the task

In theory and in practice what this means is there is an important interaction between the duration of heat exposure and **effectiveness** (and to some extent efficiency), i.e. if exposure is shorter, then faster heat transfer methods, i.e. steam, will be more effective, however, when the exposure duration is sufficient for the target and heat source to equilibrate, then there will be no difference in the effectiveness of different energy transfer methods (Merfield, 2006). A practical example of long duration application is in pre-crop emergence foliar thermal weeding in drilled vegetables (i.e. stale seedbeds), where long ‘hoods’ are used to keep the steam or hot air as close to the weeds as possible for several seconds, thereby allowing most of the energy to be transferred. In comparison, in perennial crops, e.g., vines, apples, the presence of the plant stems and supporting posts makes the use of long hoods impractical, so the heat has to be 'blown' (forced convection) at the intrarow so that there is only a short exposure time, so a fast energy transfer medium, i.e. steam, is required for maximum effectiveness. This means is that the energy transfer medium, i.e. hot air or steam, needs to be matched to the application method rather than there being any inherent advantage of steam vs. hot air.

## 6.2. Engineering / mechanical issues of flame vs. steam

Generating hot air, even in large quantities, e.g., 500 kw, can be mechanically very simple, only requiring a gaseous fuel such as LPG, a pressure / flow regulator and burners, all of which are simple engineering. Using diesel or renewable substitutes requires only marginally complex machinery. Generating steam generally requires a pressurised steam boiler, which is a comparatively complex and substantial machine (see Figure 2) with inherent safety risks, so it therefore needs various safety mechanisms.

Hot air is therefore the main choice for foliar thermal weeding. However, due to the overall low efficiencies of foliar thermal weeding (Merfield, 2006) every conceivable alternative energy transfer method, apart from ionizing radiation, has been tried and found wanting.

## 6.3. Alternatives to flame and steam

For example, the use of ultraviolet (UV) light to kill weeds has been investigated in Denmark and while patents were granted in 1996 the technique has not been commercialised (Fox 1996). Microwave radiation has also been researched (Diprose & Benson, 1984b; Vela-Múzquiz, 1984; Zanche *et al.*, 2003; Sartorato *et al.*, 2006) but has not resulted in any practical machinery. The use of lasers to cut weed stems has been investigated (Heisel *et al.*, 2002), electrocution has been studied (Diprose & Benson, 1984b, 1984a; Vigneault *et al.*, 1990) as has freezing using liquid nitrogen and carbon dioxide snow (Fergedal, 1993). The use of microwaves for soil disinfestation has also been trialled and found impractical due to the large energy use compared with direct thermal techniques (Mavrogianopoulos *et al.*, 2000).

All these approaches suffer from a range of problems (for example, safety issues, and low overall efficiencies due to multiple energy conversions limited by Carnot's theorem), that make them uneconomic or impractical for foliar thermal weeding (Merfield, 2006) and the same issues equally apply to ISTW. This is why, for foliar thermal weeding, open flame weeders are almost the only design used in practice.

### 6.3.1. Infrared thermal weeders

The only viable alternative to open flames used in thermal weeding is infrared. Infrared is a form of light i.e. electromagnetic radiation, with wavelengths longer than those of visible light, extending from the nominal red edge of the visible spectrum at 0.74 to 300 µm. The infrared light is typically generated by heating ceramic elements to red heat by burning LPG gas. Infrared heaters, slightly confusingly do therefore contain open flames, but these are confined to the ceramic elements, and do not extend to the weeds or other heat target. This means that with standard flame weeding the majority of the heat is transferred from the source to target by forced convection, while in infrared weeders it is by infrared light, i.e. photons.

There have been a small number of papers comparing infrared with flame weeders, which found that on an equal energy basis, they were generally comparable, with infrared having the edge when treating small weeds and flame with larger weeds (Parish, 1989a, 1989b; Ascard, 1998; Juroszek *et al.*, 2002; Rifai *et al.*, 2003a; Rifai *et al.*, 2003b). This is explained in terms of the differences between radiation and forced convention. While it is generally considered that radiation is a more efficient means of transferring heat to plants than forced convection, convection has the advantage when the weeds are larger because it can penetrate the crop canopy, while infrared, being a form of light, can only heat the top of the crop canopy as the top most leaves literally shade the leaves underneath, just as they do for visible light, therefore protecting them from the heat. Farmers may well need or want to treat weeds when they are large enough to start shading each other which puts infrared at a disadvantage, and in addition, the ceramic elements are somewhat fragile and therefore susceptible to breakage, which in an agricultural setting where three point linkage machinery is often subjected to significant shocks, especially during transport, is not ideal. Infrared is therefore less popular than flames.

For the purposes of ISTW infrared is also worth considering, and has been trialled, (Ed Peachey, Associate Professor/Senior Research, Weed Science, Oregon State University, USA, pers. comm.). However, and in addition to the issues surrounding the delicate nature of the ceramic plates, for infrared systems to be used for ISTW, the soil would have to be exposed one aggregate deep, because the infrared light can only heat the surface of the soil. Alternatively the soil would have to be mixed during exposure, but because of the same surface heating effect, it is considered that such extensive mixing would be required to ensure all of the soil aggregates are heated sufficiently that such an approach would not be practical.

A final issue with infrared systems is the rate of energy transfer and thus heating is determined by the temperature of the thermal source. To expand, high temperatures are **not** fundamentally required as a target can be heated to a given temperature by using a heat source of the target temperature as, given sufficient time, the target will equilibrate with the heat source, without any potential for overheating. The 'problem' with this, from a practical perspective, for target temperatures at the thermal death point of plants, i.e. 60-90°C the time taken to heat the weeds would be unacceptably long. The advantage of high temperatures is that it increases the rate of energy transfer, i.e. it increases the Wattage, thereby heating the target more quickly, but at the expense of overheating the target, and/or loosing heat through other means.

### 6.3.2. Hot air and steam are the only viable approach

So while infrared does have a role in foliar thermal weeding, it is not considered to have a role in ISTW, and therefore, as all other thermal techniques are considered inadequate, especially in terms of energy efficiency and simplicity, only steam and hot air are considered viable energy transfer media for ISTW.

## 6.4. Existing hot air soil heaters: the 'Cultivit'

In addition to the above analysis that indicates that hot air could be a viable alternative to steam for ISTW, the use of hot air for soil pasteurization has already been the subject of research, (Runia & Greenberger, 2004, 2005; Runia *et al.*, 2006; Runia & Molendijk, 2010) and there is a commercial hot-air soil pasteurisation machine in use by growers: the 'Cultivit' produced by VDL Cultivit bv, The Netherlands www.vdlcultivit.nl (Figure 5). This machine was designed to replace chemical soil fumigants for nematode control, and uses a rotary spading tiller to mix the hot air with the soil as it travels across the soil.


Figure 5. VDL Cultivit, travelling, hot air, soil pasteuriser.

While the Cultivit has been designed for whole soil pasteurisation to a depth of up to 30 cm, and is therefore wholly unsuitable for ISTW that aims to heat only a small volume of intrarow soil, it demonstrates the thermodynamic, mechanical, agronomic and commercial viability of using hot air for soil pasteurisation, using of diesel fuel and heat exchangers so that only clean air is passed through the soil.

# 7. Conclusions

ISTW is considered to have the potential to be a valuable alternative to and replacement for herbicides, but probably only if significant improvements can be made to its energy efficiency, work rates and making the machinery more practical and safe for agricultural use. To achieve this, it is considered that the use of steam as the heat source is unsuitable, due to the practical and safety issues surrounding the use of pressurised steam boilers on mobile agricultural equipment and because recycling / heat from the soil is impossible. The use of hot air appears to be the only viable approach from a theoretical perspective with the practicality of hot air to heat soil demonstrated by the existence of the Cultivit hot air soil pasteurization machine.

However, to achieve the aim of making ISTW a practical technique, a considerable amount of analysis and research is required. The amount of literature / research to date on ISTW is about 15 papers, both journal and conference. While addressing important aspects of ISTW, the research is mostly ad-hoc in that it is not guided by a clear theoretical framework or part of a coherent project with strategic outcomes.

In addition the science is multidisciplinary, involving weed science, soil science and engineering. These are three very different sciences, operating under quite different theoretical frameworks, cultures and at different stages of their phylogenetic development (Johnson, 2006) making for challenging integration.

Although the main objective of ISTW is weed management, the science of weed management probably has the smallest contribution to make to ISTW as its primary task is to check seed mortality. While the general engineering required is well established, it is a hybrid of agricultural engineering and boiler / burner engineering, which are almost completely separate areas so the boiler and burner engineering needs to be considerably changed from what works in static industrial situations to a viable agricultural machine, which requires a quite different mindset. Within soil science the sub-discipline principally involved is the minor sub discipline of soil physics (soil science being dominated by soil chemistry) and in turn its minor sub-discipline of soil thermodynamics, of which artificial soil heating is only a small section compared with natural soil heating, so experts in this area are uncommon (Hillel, 1980).

Bringing together the necessary scientists and engineers in a sufficiently sized project to fully research the issues and design suitable engineering solutions is therefore a significant exercise. However, continuing to proceed in an ad-hoc fashion is considered unlikely to move ISTW forward sufficiently quickly.

# Section 2.
# Hot air vs. steam for ISTW

## 1. Summary


- All current intrarow soil thermal weeding (ISTW) systems use steam, but there are a number of reasons to use hot air instead, key of these being mechanical simplicity and heat recovery which could significantly reduce energy consumption.
- The engineering optimum heat exchanger design for air to soil (gas to particulate solid) is a counter-flow, direct-contact design, of which fluidised-beds are the best design for large amounts of dense particulates, such as soil.
- Such heat exchangers can both heat / cool soil and air equally effectively, i.e. full heat recovery is theoretically possible.
- Two separate soil heating and soil cooling heat exchangers set up in-series can be combined into a single unit. This is the foundation of the single-vessel, two-stage approach with its 'standing wave' of hot soil.
- However, the use of ex-situ heat exchangers, such as fluidised-beds, poses a number of major engineering and design problems / challenges, such as the difficulty of handling small volumes of soil and soil adhesion to machinery, which means that in-situ heat-exchangers are preferable.
- An in-situ, two stage, counter-flow, direct-contact soil and air heat exchanger conceptual design is presented that is considered to address all the fundamental engineering and design requirements for a hot-air ISTW system with heat recovery. This is based on an inverted U shaped tunnel using a sequence of horizontal axis rotating tines to mix soil with the air stream.
- The key engineering and design issues that need addressing are highlighted including the volume and pressure of air produced from the heat recovery stage, that the heat insertion point is the critical challenge, and the containment of the counter-flow air at the point of entry.


## 2. Introduction

To date all ISTW work has used steam. This is believed to be for two main reasons:

- Steam has been the almost exclusive heat source for soil pasteurization so using it for ISTW appeared 'obvious' and no or little consideration was given to alternatives;
- Because of a belief among thermal weed scientists that steam is 'better' than flame (see page 29).

However, there a number of reasons why steam may **not** be the optimum heat transfer medium for ISTW. These include:

- the engineering complexity of steam boilers;
- the large amounts of water consumed;
- the difficulty of recycling heat from the soil to improve efficiency.

The alternative is to use hot air as the heat transfer medium. This is considered to me advantageous for two key reasons:

- Engineering simplicity;
- That at a 'theoretical' level the use of hot air to heat soil can be reversed to recover the heat from treated soil, i.e. transfer the heat from soil back to air, allowing the recycling of heat, thereby significantly reducing energy consumption.

However, critical to making such an approach work is designing a heat exchange system between soil and air, that is as thermally efficient, as well as practical, as possible. Practical, in this context, refers to the machine having to operate in an agricultural environment, i.e. with limited or no specialised engineering personnel for machinery operation or maintenance and in hostile conditions, e.g., in contact with soil and exposed to the weather.

This section of the report therefore analysis the mechanical and practical issues relating to the production of steam and hot air in an agricultural field environment. The report then considers the technical aspects of heat transfer between gasses and particulate solids and the theoretical basis for recycling of heat from treated soil.

# 3. The mechanical and practical issues of generating steam vs. hot air

From an engineering perspective the generation of steam and hot air are very different, as outlined on page 30 and as illustrated by the size of the pressurised boilers in Figure 2 and Figure 3. If it is practical to use hot air as the energy transfer media for ISTW this should significantly simplify the complexity of the machinery required.

The importance of maximising simplicity in both engineering and design for agriculture can not be overemphasised for two key reasons:

- First, agriculture is a very hostile environment for machinery, as machines are exposed to the weather, particularly rain / water, and more importantly, they are exposed to soil and soil dust, which is often (depending on texture) highly abrasive, it desiccates lubricants (silt and clay dry out oil and grease), and is corrosive due to the organic acids in organic matter;
- Second, farmers and farm workers are 'jacks of all trades' and therefore need to have a wide range of skills, which means they often lack depth of skills in many areas. They may therefore only have basic machinery use and maintenance skills / understanding. Depending on legal jurisdiction, operators of pressurised steam boilers often require specific training / qualification, which many farmers don't have and may prove a barrier to the uptake of band steaming. Having untrained people using pressurised steam boilers is considered a significant safety risk, especially in an industry with an already poor health and safety record.

Therefore agricultural machinery needs to follow the KISS (keep it simple, stupid) principle (Wikipedia contributors, 2012) as much as practical, to ensure that it can function in a hostile environment while being operated by people with limited mechanical skills and presenting as small a health and safety risk as possible.

## 3.1. High water consumption

The use of steam as a heat transfer media necessitates the consumption of water in sizeable quantities, e.g., a 100 kw steam boiler can consume 100 L·water·hr$^{-1}$ with Melander & Kristensen, (2011) giving 8,000 L·water·ha$^{-1}$ as a typical amount used for ISTW. The supply of this water, either from tanks carried with the boiler (e.g., Figure 3), or via trailing hoses, adds to the complexity and reduces the practicality of the machinery. Using hot air as the heating medium avoids the use of water and its associated problems.

## 3.2. Direct-fired steam boilers

An alternative to the standard pressurised steam boiler is the direct-fired steam boiler (Merfield, 2006; Merfield *et al.*, 2009). This design uses an open vessel and so avoids the hazards associated with closed vessel (pressurised) boilers. However, the design was conceived for foliar thermal weeding, where back-pressures are purposely negligible to minimise safety risks. To be used for ISTW the design would have to be modified towards static industrial direct-fired boilers (e.g., the Johnson CurePak, http://www.johnsongas.com/industrial/concrete.asp) which produce higher pressure steam, for example the strength of the combustion chamber would have to be increased to withstand the higher pressures and fans / compressors that can provide the required combination of large air volumes and pressures would be needed. The result of this is that high-pressure, direct-fired steam boilers are as large and nearly as complex as standard pressurised steam boilers, therefore giving little advantage.

The use of direct-fired steam would still require a supply of water and therefore bring the issues involved with water supply.

Perhaps most importantly with direct-fired steam, the combustion products are mixed with the steam. Even with a very clean burning system, some of the chemical products of combustion are toxic, and it is recommended that these should not be permitted to enter the soil as they could have significant negative effects. This is not a problem for foliar thermal weeding as the steam only contacts the surface of plants and the soil and then escapes to the atmosphere. However, using a direct-fired steam boiler for ISTW would result in all the combustion products entering the soil. The only solution to this is to use a heat exchanger to transfer the heat in the direct-fired steam to another gas stream free of combustion products. However, transferring the heat to another steam stream is complicated by the phase change of liquid water into vapour, meaning that much of the advantage of the direct fired steam system over a pressurised boiler would be lost. Transferring the heat from the steam to air, makes no sense as the steam adds nothing to the process, rather it complicates it. Therefore direct-fired steam boilers are not considered a viable technology for ISTW.

## 3.3. Steam vs. air as a heat transfer medium

While the use of hot air from a machinery design perspective has considerable merit, there are other issues than mean that hot air is **not** a completely straight forward replacement for steam in ISTW.

### 3.3.1. Keeping combustion products out of the soil

As discussed on page 34, it is undesirable for combustion products to enter the soil. Therefore while it would be simpler from an engineering perspective to use the hot combustion gas stream to directly heat the soil, this should be avoided, and a heat exchanger will be required to transfer the energy to 'clean' air which can then be safely passed through the soil. Exchanging heat between two gasses, especially if they are similar (e.g., in terms of their mass, volumes etc.) and there is no phase change, is mechanically straight forward and when using counter-flow heat exchangers the process can achieve efficiencies of almost 100%. Therefore while the use of a heat exchanger slightly increases the mechanical complexity, the effect on the overall efficiency of the process will be small. In addition this approach is already used in the Cultivit machine (page 31).

### 3.3.2. Treatment duration and confinement

As detailed on page 29, when the target to be heated can be confined for a sufficiently long duration for the heat source and target to equilibrate, then, there will be no difference in the effectiveness / efficiency of different heat transfer media, i.e. with suitably designed application machinery that keeps the hot air or steam in confined contact with the soil for long enough both will have the same efficiency.

All of the band steaming applicators developed for field work, use some form of confinement system to keep the steam in contact with the soil for a period of time. The Danish design (see page 24) uses an inverted U shaped tunnel (Figure 3), while the Swedish design uses a flat steel sheet sitting on the soil surface (Figure 2). As these existing band steamers already use confinement systems to maximise the treatment duration (within practical limits), hot air will be able to transfer heat as effectively as steam if sufficiently long confinement durations are used. However, the treatment duration for hot air is likely to be longer than steam due to a number of factors.

## 3.4. The physical issues of hot air as a heat transfer medium in ISTW

### 3.4.1. Heat capacity

A key issue of using hot air for heat transfer is its low heat capacity ('energy density'), which means a greater mass (and therefore volume) of air is required to transfer the same amount of energy / heat into the soil compared with steam, particularly when the latent heat of condensation is included.

The volume of a gas in relation to its mass is determined by its specific volume (an intensive property) which is also affected by pressure and temperature, i.e., there is a three way interaction between pressure, temperature and thermal energy content. Higher temperatures axiomatically increase the amount of thermal energy of a gas and will also increase the volume and/or pressure depending on whether the gas is confined or not.

### 3.4.2. Pressure

Higher pressures increases the mass per volume of gas, thereby increasing the amount of energy it can carry. Compressing a gas also directly increases its temperature, but the increase is small compared with the total energies involved in ISTW so it can be generally ignored.

However, within the design parameters of hot air ISTW, it is not desirable to increase the pressure too far beyond what is required to propel the gasses through the machinery and the soil (e.g., 1 bar). This is because it increases the engineering complexity and higher air pressures also create higher velocity gasses when decompressed which means they could cause the soil to be excessively agitated when being treated, e.g., the soil may be blow out of the treatment system.

### 3.4.3. Temperature

The combustion temperature of LPG is 1,970°C and diesel 2,100°C so producing high temperature air is unproblematic. However, such high temperatures will melt or significantly deform most metals, and also destroy many common thermal insulation materials, e.g., glass wool. Only specialised high temperature materials such as such as ceramic wool refractory insulation, and high cost metals, e.g., titanium, can survive such temperatures. Therefore the use of very high temperatures through to point of use (as opposed to the combustion chamber) also increases engineering / design complexity and cost, the opposite of what is desired. Therefore using lower temperatures at the point of application, e.g., 400°C would be preferable as these will simplify machinery design and engineering. Lower temperatures are simple to achieve by adding cooler unheated air to the hot air stream. A temperature reduction can also be achieved as part of the heat exchange process, by increasing the mass / volume of clean air passing through the exchanger, a process that can also help to ensure maximum efficiency of the exchange process. However, the increased gas volume resulting from lowering the temperature may cause other problems.

### 3.4.4. Volume

If high pressures and temperatures are excluded by the design parameters, then the alternative means of transferring sufficient heat using air, is by increasing the volume. However, this also creates design issues: on the engineering side, large volumes of low pressure air require pipe and ducts with large cross-sectional areas; and on the application side trying to pass a large volume of air through a small volume of soil to be treated creates practical issues, e.g., speed of operation. Therefore increasing the volume of hot air also has constraints and issues.

### 3.4.5. Pressure vs temperature vs volume

Therefore the desire for engineering simplicity and the practical restrictions of agricultural puts quite significant design restrictions on the maximum pressure, temperature and volume of hot air that can be used for ISTW. To evaluate these requires detailed engineering calculations and empirical verification beyond the scope of this report.

However, there is an important additional benefit of using hot air over steam, that of heat / energy recycling, which may mean that the issues associated with hot air heating are worth overcoming.

## 3.5. The potential for heat recycling

One of the primary drivers for ISTW is its much lower energy requirements compared with standard whole-soil steaming, due to only a shallow depth of intrarow soil being heated for a short period (Melander *et al.*, 2002b; Melander *et al.*, 2002a). However, band steaming still consumes considerable amounts of fuel, e.g., 570 to 850 $L \cdot diesel \cdot ha^{-1}$ and it has slow work rates, e.g., 0.1 to $1.25 \cdot ha \cdot hr^{-1}$ (Hansson & Svensson, 2004; Hansson & Svensson, 2007; Melander & Kristensen, 2011). At this level of productivity the use of band-steaming is mostly restricted to high value organic horticultural or specialist crops (e.g., vegetable seed) where the cost of band steaming is significantly less than the cost of the hand-weeding that it replaces. However, it is considered that all other weed control methods other than hand weeding, are likely to be (considerably) less expensive than band steaming. Therefore, band steaming will only be economically viable where hand weeding is required. To make ISTW more economically viable and be able to replace herbicides, the cost and/or the work rate will have to be significantly improved.

### 3.5.1. Heat production is '100%' efficient

It is not considered possible to improve the **direct** energy efficiency of band steaming. The efficiency of heat engines as determined by Carnot's theorem does not apply to thermal weeders as they are not heat engines in the technical sense, as the are not using heat to do work, they are only producing heat and transferring that heat to the target. As the final form of all energy conversions is heat, thermal weeders, in terms of generating heat are effectively 100% efficient (as are all 'heaters'), which is axiomatically impossible to improve.

However, at a practical level, there are inevitable inefficiencies in heat production, e.g., a boiler heats up in use, some energy is lost up the chimney with the exhaust gasses, and due to practical and economic restrictions insulation is not perfect, so the total efficiency of heat production and supply is lower than 100%. With pressurised steam boilers efficiency some of the heat is lost with the combustion gasses up the chimney, which combined with other heat losses mean efficiencies of 70-90% are typical.

### 3.5.2. Lower energy loss with hot air production than pressurised steam

On of the key energy efficiency benefits of direct-fired steam boilers over pressurised boilers (page 34), is there is no loss of energy with the exhaust gasses up the boiler chimney (Merfield, 2006). The use of hot air as the heat source shares this same benefit, i.e., no chimney heat loss. This is not negated by the need to transfer the heat to a clean air-stream (page 35) as there is close to 100% efficiency transferring the heat between the two air streams. Therefore the efficiencies of pressurised steam boilers, discussed above, can be improved upon by hot air systems.

### 3.5.3. High efficiently of heat transfer to soil

The main inefficiencies in thermal weeding occur when not all of the heat reaches the target. For foliar thermal weeding the main routes of loss being to the atmosphere and the soil and these can be in the order of 99% of the heat generated (Merfield, 2006). In comparison band steaming losses are much smaller e.g., the range of 0-9% in a well confined system, being mostly due to loss of steam to the air (Kristensen *et al.*, 2005).

### 3.5.4. Recovery / recycling of heat

Therefore as conversion of fuel energy to heat is 100% efficient, modern steam boilers can achieve high conversion efficiencies, e.g., 90% and 90-100% of the heat in the steam can be transferred to the soil there is limited room for efficiency improvements in existing designs. One route would be the gains to be made due to eliminating pressurised boiler chimney losses when using hot air (see page 37) however, these are probably moderate, e.g., 10%. Therefore, the only conceivable means to significantly improve the efficiency of ISTW system is to recover / recycle the heat from the treated soil and re-use it, rather than leaving the heat in the soil in the field as is done with all existing ISTW / band steaming systems. This is considered a viable approach because the transfer of heat between steam or air and soil, and the reverse, from soil to air, is **not** governed by Carnot's theorem and its efficiency limits, rather, the thermodynamics of heat exchangers and Fourier's law apply, whereby, with a well designed heat exchanger (e.g., counter flow) all of the thermal energy in the source material can be transferred to the receiving material.

While effective as an initial heat source, steam is unsuitable as a heat sink to recover heat from soil due to two reasons:

- the use of latent heat of condensation to transfer energy to the soil, which cannot be reversed without an external energy source;
- the water in the steam is absorbed by the soil, which also requires an external energy source to release / recover it.

In comparison, the process of using hot air as heat sink to recover the heat from soil should ‘simply’ be the reverse of the process by which the heat was initially transferred to the soil, as there is no phase change and no absorbtion of the air by the soil.

At a ‘theoretical’ level, if heat recovery from the soil is highly efficient then the total energy / fuel use of an ISTW could be very low as fuel would only be required to replace the thermal losses from the system, e.g., due to ‘imperfect’ insulation. However, there are a number of factors that mean the total efficiency of the system will be lower than what could ‘theoretically’ be achieved, with the exchange of heat from air to soil and particularly back to air again being considered the key factor.

### 3.5.5. The complexity of heat exchange between soil and air

The exchange of heat between a gas (such as hot air) and a particulate solid (such as soil), and its reverse, (i.e., soil to air), is more of an engineering challenge than, for example, heat exchange between two liquids or two gasses. In addition, the highly variable nature of soil, particularly aggregate size, and the requirement for the two-way heat exchange to occur in an agricultural setting makes the process particularly challenging. This, coupled with the engineering / design restrictions on the temperature, pressure and volume of the hot air means that detailed thermodynamic calculations and empirical testing of hot air based ISTW will be required that are beyond the scope of this report.

# 4. Air and soil, heat exchange systems

## 4.1. Heat exchanger fundamentals

The science of heat exchangers is well established and can mostly be accurately mathematically modelled, except for more complex materials and flows where a level of approximation is required.

There are two primary designs of heat exchanger:

- **Parallel-flow**, where the two materials enter the exchanger at the same end, and travel in parallel to one another to the other side;
- **Counter-flow**, where the two materials enter the exchanger from opposite ends.

The counterflow design is the most efficient as it can transfer practically all the heat due to the fact that the average temperature difference at any point along the exchanger is greater than parallel flow. At a theoretical level a counter-flow heat exchanger can have 100% efficiency, i.e. all the heat is transferred from one medium to the other, although in most cases, efficiency is slightly lower due because of diminishing economic returns of trying to transfer the last few joules of energy.

To maximise efficiency, the surface area between the two media exchanging heat needs to be as large as possible while minimising flow resistance. Depending on the type of medium, i.e. solids, liquids or gasses, the two media are either in direct-contact, or physically separated by a barrier, e.g., are in pipes.

Where the two media are in contact with each other this is referred to as a 'direct-contact heat exchanger'. This is the predominant design used where heat has to be exchanged between a particulate solid and a gas or liquid, such as soil and air (unless the two media are physically or chemically incompatible and have to be kept separate).

### 4.1.1. Particulate and gas, direct-contact, counter-flow, heat exchanger

The basic approach of a particulate and gas, direct-contact, counter-flow heat exchanger is to have the particulate descending a vertical tower under gravity, with the gas flowing in the opposite direction, i.e., up the tower, under pressure, with zones of disengagement top and bottom (Figure 6).

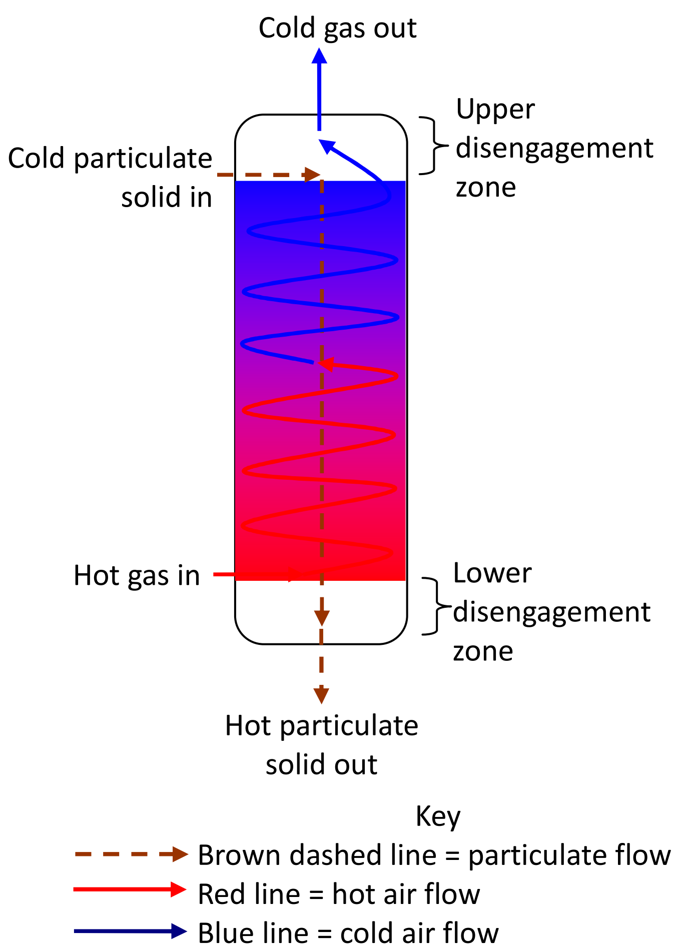



Figure 6. Particulate and gas, direct-contact, counter-flow, heat exchanger (heating the particulate / cooling the gas).

There a many variations on this fundamental theme that are tailored to the specific properties of both the particulate and the gas, e.g., the density, particle size, flow rates, volumes, temperature etc. For example, with lower density solids and higher gas flow rates the particles can be introduced so that they 'rain' down the tower i.e., the particles are separate from each other during transit through the system.

With higher density solids, such as soil and coal, fluidised-beds are used where the particulates 'fill' the heat exchanger and the gas is forced through the mass of particles (i.e., under pressure) causing them to behave like a liquid. In terms of heat exchange between a dense solid, such as soil and higher pressure gases, fluidised-beds are generally the most efficient means of heat exchange and also the most effective in terms of the size and simplicity of the machinery.

Heating vs. cooling the particulate solid is simple to achieve by reversing the temperatures of the two streams, i.e., solids always move down the tower and gasses up, but to heat the solid, the solid enters the tower in a cold state while hot gas is introduced at the bottom, to cool the solid, hot solid enters the top of the tower and cold gas enters at the bottom. In a correctly designed system both directions of heat exchange are equally efficient.

Therefore, the fundamental task in designing a hot air ISTW system is to design a particulate to gas, direct-contact, counter current heat exchanger system that also meets the constraints of agricultural machinery design in terms of being simple, reliable, robust, low maintenance, etc., i.e., following the KISS engineering principle.

## 4.2. Designing a heat exchanger for hot air ISTW

As soil is a dense, particulate solid, a fluidised-bed approach initially appears to be a good starting point for a hot air ISTW system. However, there are a number of problems with using fluidised-beds, so an analysis of the pros and cons is helpful in illustrating the design problems with hot air ISTW.

### 4.2.1. Two heat exchangers in-series

The starting point for an analysis of the use of fluidised-beds for hot air ISTW, is to pass soil that has been removed from the intrarow through one fluidised-bed heat exchanger to heat it up, then pass it through a second fluidised-bed to cool the soil down and return it back to the intrarow while recovering the heat into the air stream, which is then passed to the first fluidised-bed that is heating the soil up, (Figure 7).

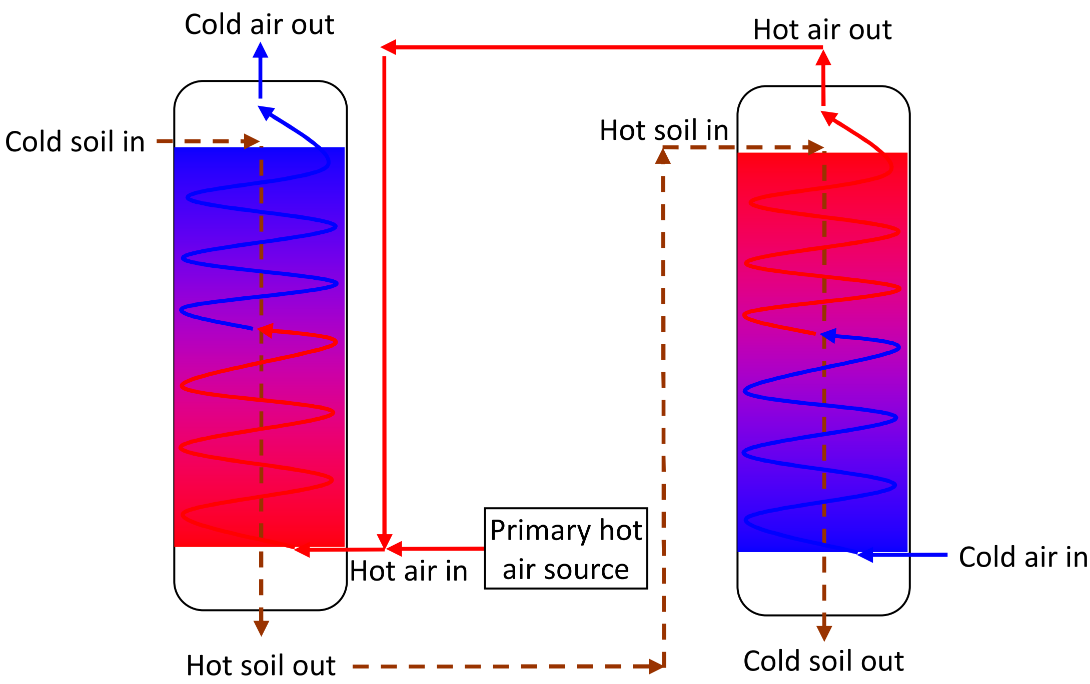



Figure 7. Two, in-series, counter-flow, fluidised-bed, direct-contact, heat exchangers, the first to heat cold soil using hot air, then, the second to cool the soil and (re)heat the air which is passed back to the first heat exchanger.

No system can be truly 100% efficient as there are inevitable losses of heat, e.g., insulation is imperfect, so such a system requires both an initial heat source to start it and then to replace heat losses. This is shown in Figure 7 as the ‘primary hot air source’.

### 4.2.2. Single-vessel two-stage heat exchanger

As the two heat exchangers in Figure 7 are in-series, the design can be simplified into a single-vessel, by ‘stacking’ the two heat exchangers on top of each other, placing the primary heat source half way up the new single heat exchanger creating a single-vessel heat exchanger with two stages, i.e. a heating and a cooling stage (Figure 8). The join between the two heat exchangers is more complicated than this simple illustration, but these issues can be set aside for the current purpose of showing the heating and cooling process can be performed as a single operation.

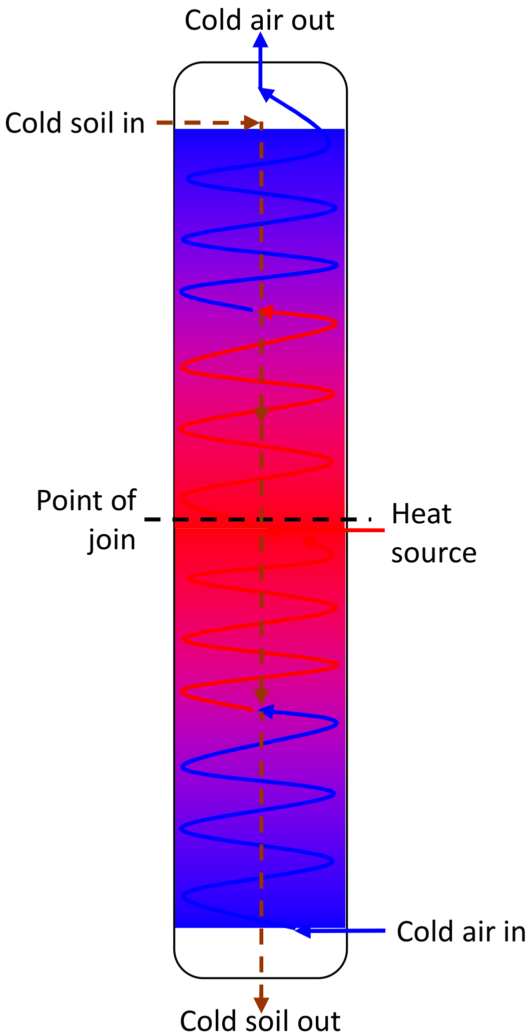



Figure 8. Single-vessel, two-stage, counter-flow, direct-contact, heat exchanger that heats then cools soil, created by joining the two separate heat exchangers in Figure 7.

This single-vessel design highlights the key concept of a ‘standing wave’ of hot soil, i.e. soil is heated up and then cooled down in a continuous process, i.e. at any one point along the vessel the temperature is constant, even though soil is continuously moving through it.

While ‘theoretically’ this is a good solution to the heating and cooling problem of soil, there are a number of issues with it. These fall into two categories:

- The difficulty of controlling fluidised-beds when the particulate is highly variable, in terms of density, particles size, moisture content etc.;

- Ex-situ soil heating, i.e. removing the soil to be heated from the field, heating it, and then returning it to the field.

### 4.2.3. Fluidised-beds and their limits

While fluidised-beds are an optimal engineering solution for heat exchange between a particulate solid and a gas at a 'theoretical' level, in practice, the physics of the interactions between particle and gasses in fluidised systems can be very complex, especially where the particles are not uniform. Therefore, fluidised-bed systems have to be tailored to the precise properties of the specific solid and gas in question to get them to work effectively. Soil is a highly variable material even over the space of a few meters in a single field. The level of variation is such, it is considered that it would be very difficult to design a fluidised-bed system for soil heating, especially within the engineering constraints of agricultural equipment (Deborah V. Pence, Professor of Mechanical Engineering, Oregon State University, pers. comm.).

To try and overcome the precise engineering requirements of fluidised-beds, and similar direct-contact systems the inside of the heat exchange vessel can be modified with baffles or similar devices to assist with the flow of soil (Figure 9).

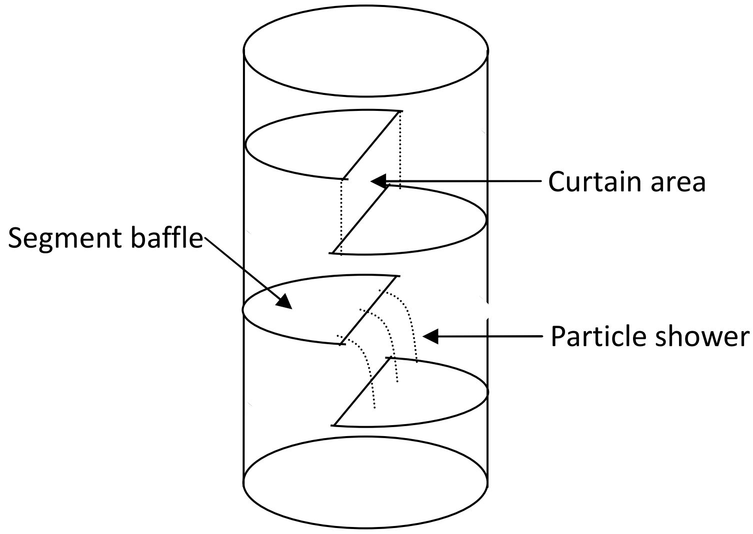



Figure 9. Conceptual schematic of a baffle tray column.

While such devices can be very effective for the right materials, the approach is not considered suitable for soil, due to many soils having adhesive properties, i.e. they stick to solid surfaces, even stainless steels, and including soil already adhering to surfaces, so thick layers of hard compacted soil can build up on machinery.

This is one of the many properties of soil that make ex-situ handling highly problematic, especially for small volumes of soil.

### 4.2.4. Ex-situ soil heating problems

#### 4.2.4.1. Ex-situ soil handling issues

The three main classes of soil texture, sand, silt and clay, have widely varying properties, which in turn are moderated by the moisture content. For example:

- sands are highly abrasive, and have low adhesion so don't stick, even when wet;
- clays are only very slightly abrasive, but they have exceptional powers of adhesion when wet but no adhesion when dry;
- silts have properties in-between clays and sands.

Soils are therefore very difficult materials to handle, for example:

- they may or may not stick to the handling equipment depending on texture and moisture content, and when they do stick they can build up sufficient thicknesses to block equipment;
- soil adhesion is greatest where the soil flow is at 90° to the impact surface, i.e. the soil hits the surface head on, and is least where the soil and the contact surface are parallel, i.e. the soil is sliding over the contact surface;
- soils can be highly abrasive so high wear or abrasion resistant components (e.g., rubber) are required;
- many soils contain significant quantities of gravel and stones, of a wide range of sizes, which will block small orifices, and exert large point forces puncturing thin materials;
- etc.

All of these mean that treating soil ex-situ can considerably increase the complexity of machinery.

For ISTW in particular, the small volumes of soil being treated, i.e. just the intrarow soil, means there will be a large contact area per volume of soil, due to the surface-area-to-volume ratio. This means that adhesions problems will be more problematic than for large soil volumes as the proportion of soil adhering to the machinery may represent a significant proportion of the total soil volume being handled, e.g., >30%.

Approaches such as the baffle tray column (Figure 9) where the soil drops onto a horizontal baffle, creates optimum conditions for soil build up. Ideally all soil contact with mechanical parts should be in parallel.

Soil adhesion and consequent build-up means that all areas that soil contacts have to be accessible for cleaning, which due to the considerable hardness that packed soil can achieve, means that water washing may be insufficient and physical removal, e.g., with steel tools, could be required. That means that all closed vessels, such as the vertical tower heat exchangers, discussed above, would require ports that permit a person to access all the internal areas of the machinery.

The very complex and variable nature of soil, can mean that soil from one part of a field, will flow through a machine without difficulty, while apparently similar soil from a different part of the same field, can block a machine in a few minutes, e.g., due to small but critical changes in soil moisture. This means that all soil handling components have to be designed so that:

- soil blockages are prevented or automatically cleared; and/or
- they are automatically monitoring for soil blockages and machinery shut down when blocks occur; and/or
- they can be viewed and therefore monitored by the operator, who can take the necessary action.

These, and other requirements put a significant constraint on the fundamental engineering designs of all agricultural soil engaging equipment and equally apply to machinery designed for heating / drying soil.

#### 4.2.4.2. Engineering designs capable of ex-situ soil handling - rotating cylinders

There are a only a very small number of fundamental engineering designs that are suited to ex-situ soil heating and can deal with its multiple, complex and difficult handling properties. Of these, the rotary cylinder dryer, commonly called a 'rotary dryer' is the predominant type, and consists of a horizontal cylinder with internal baffles, that rotates around the long / central axis of the cylinder, so that the baffles pick up the particulate solid as the cylinder rotates and then drops the material into the airstream (Figure 10).

A related approach is the 'revolving screen separator' which is commonly used for sieving / separating large quantities of soil into different size grades (Figure 10). While revolving screens are not used for heating soils, they are included to illustrate use of a revolving cylinder as a primary means of manipulating soil ex-situ for heating, drying and sieving.

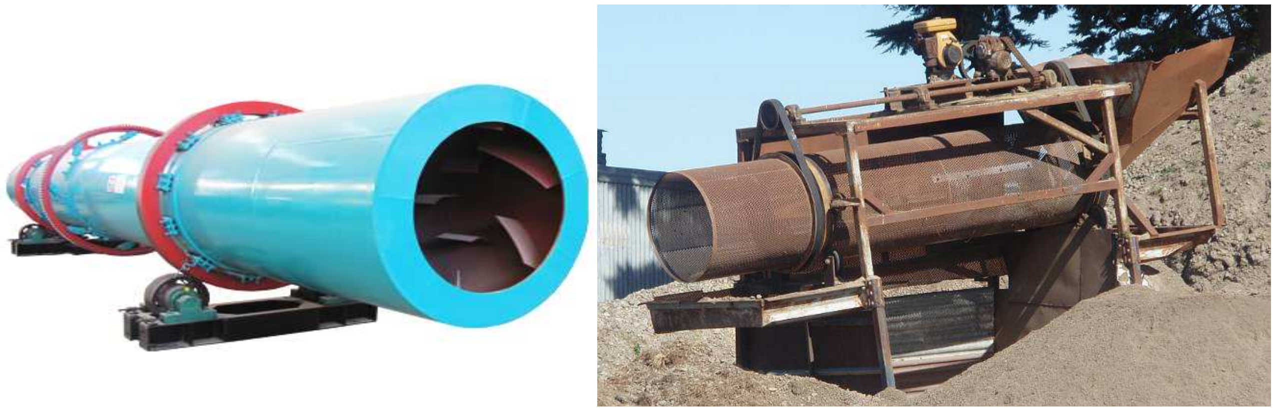


Figure 10. Left, rotary cylinder dryer (source http://www.zd-dryer.com/Dryer/2.html); right, revolving screen separator.

While rotary dryers are very effective for their primary purpose of drying soil and other particulate solids, there is a considerable difference in the physics of drying vs. heating soil, which mean that the efficiency of heat transfer in a rotary dryer, were it used for soil heating, would be significantly lower than the heat exchangers discussed above due to the lower amount of contact between gas and soil. The system can be re-engineered to improve the efficiency, e.g., slowing the gas flow through the cylinder, and/or reducing the internal volume of the cylinder in relation to the amount of soil flowing through it. However, such approaches still leave a number of problems, the two key ones are the soil adhesion issue and problems with ex-situ soil heating as a whole.

Most rotary dryers are very substantial machines, which a person can easily walk inside, allowing for 'easy' cleaning. The volumes of soil being treated in an ISTW system would be much smaller, requiring much smaller cylinders, e.g., a diameter of 300 mm, meaning that soil adhesion and therefore the cleaning issues discussed on page 42 would have to be addressed.

### 4.2.4.3. Ex-situ soil handling: the volume and displacement problems

In addition to the difficulties described above with ex-situ soil heating in terms of finding an engineering design that meets the design requirements in terms of both soil heating and meeting agricultural practicalities, there is an additional problem associated with ex-situ soil heating. Axiomatically the technique requires the soil to be removed from the field surface, then treated, and returned to the field. There are a number of problems with this need to remove the soil from the field, but two, the handling and displacement problems are considered the most significant.

### The small soil volume handling problem

Lifting and handling small volumes of soil, such as the 5×5 to 7×7 cm cross sectional area of the intrarow, is much harder than handling large volumes of soil, due to multiple issues such as the surface to volume ratio, adhesion, stones, plant residues, etc. Creating a continuous and constant flow of small volumes of soils is even harder, i.e., as opposed to intermittent flows, such as digging soil up with a spade or mechanical bucket. Existing agricultural machines that attempt comparable tasks, e.g., root vegetable harvesters, are notorious for being very complex, i.e., many moving parts, which are prone to wear, and therefore have comparatively short lifespans compared to comparable in-situ machines such as powered tillers, e.g., rotovator.

While it is not impossible to lift and transport small intrarow soil volumes into a heat exchanger and then put them back into each intrarow in the exactly the same amount as was removed in each row, the solution is likely to require complicated rather than simple engineering, which is the opposite of what is desired, i.e., it violates the KISS principle. This issue alone is almost sufficient to rule out ex-situ soil heating.

### The soil displacement problem

The second issue with all ex-situ heating approaches is that they require a certain volume of soil to be able to work effectively, e.g., a fluidised-bed without enough soil to form a bed, is not going to work. With the small volumes of intrarow soil being removed, e.g., cross sectional area of 25 to 50 $cm^3$, potentially tens of meters of intrarow soil would have to be removed to sufficiently fill the machine for it to be able to function correctly and heat the soil, before, the soil can be returned back to the field, i.e., there is a horizontal displacement of soil. This would created an area of field from which soil had been removed at the start of operations, while at the end of operations, there would be excess soil in the machine that needs to be discharged.

Once a machine is in operation this displacement is considered to be of limited consequence, including within-field headland turning, but when starting and stopping at the start and end of field operations, it creates a moderate usability issue. One solution would be to keep the machine full of soil between each use, but due to the corrosive nature of soil, especially in the presence of water, and multiple additional problems created by soil left within machinery, this approach not considered viable. Conversely, best practice for the maintenance of agricultural equipment is completely the opposite, i.e. that machines should always be fully cleared / cleaned of soil after use.

It is also considered bad practice to transport soil from one field to another as it is a well established means of vectoring pests, even though the soil should contain no viable weed seeds due to heat treatment, and other soil borne pests should also be killed, it is still considered a less than ideal practice.

In addition, soils of different types would end up being mixed at the start of operation, e.g., a stony poor quality soil inserted into a high quality non-stony soil. It is considered that producers are likely to have significant reservations about this kind of inter-field and especially inter-farm soil transport, even though most ignore the well established issues of soil transport and associated pest contamination on tillage and other field operation equipment.

Probably the most practical solution is to start and end the treatment in the same place, i.e. after the final run of the field, the ISTW machine returns to the starting point where the intrarow soil is missing and replace it with the residual soil in the machine. However, this is still not ideal, as start and finish points can be some distance apart adding extra operating time and other inconveniences and it may be difficult to ensure that the residual soil to be 'dumped' at the end of the run exactly matches the amount of soil removed at the start of operations.

While this ex-situ soil treatment volume issue is not considered insurmountable, from both engineering and usability perspectives, it is one more issue that further adds to the problems of ex-situ treatment that make it unappealing. The alternative is therefore to use in-situ soil heating.

## 4.2.5. In-situ soil heating

### 4.2.5.1. In-situ soil handling - the tillage precedent

While ex-situ soil handling is highly unusual in agriculture, in-situ is the norm, i.e. practically all forms of tillage are based on in-situ soil 'handling'. There is therefore a large range of very well developed and established means of manipulation soil in-situ to achieve a wide range of effects, such as inverting the soil with ploughs, reducing compaction / pans with subsoilers, mixing and breaking down soil aggregates (creating a tilth) with rotovators (rotaryhoes), vertical power harrows, spading machines (rotary and true digging action), a multitude of spring and ridged tine cultivators and rollers of many different types. This means there is a very substantial amount of theoretical and practical knowledge that can be leveraged for in-situ soil heating for ISTW.

#### 4.2.5.2. Turning an ex-situ solution into an in-situ solution

The key objective is therefore to translate the positive aspects of the ex-situ, single-vessel, two-stage, counter-flow, direct-contact, heat exchanger concept (page 41 and Figure 8) into an in-situ solution. Conceptually this achieved by rotating the counter-flow heat exchanger in Figure 8 on its side and instead of using gravity to move the soil through the vertical exchanger vessel, instead the vessel itself is drawn through the soil, the 'equal and opposite' result of which is that soil also moves through the vessel in the opposite direction (Figure 11).

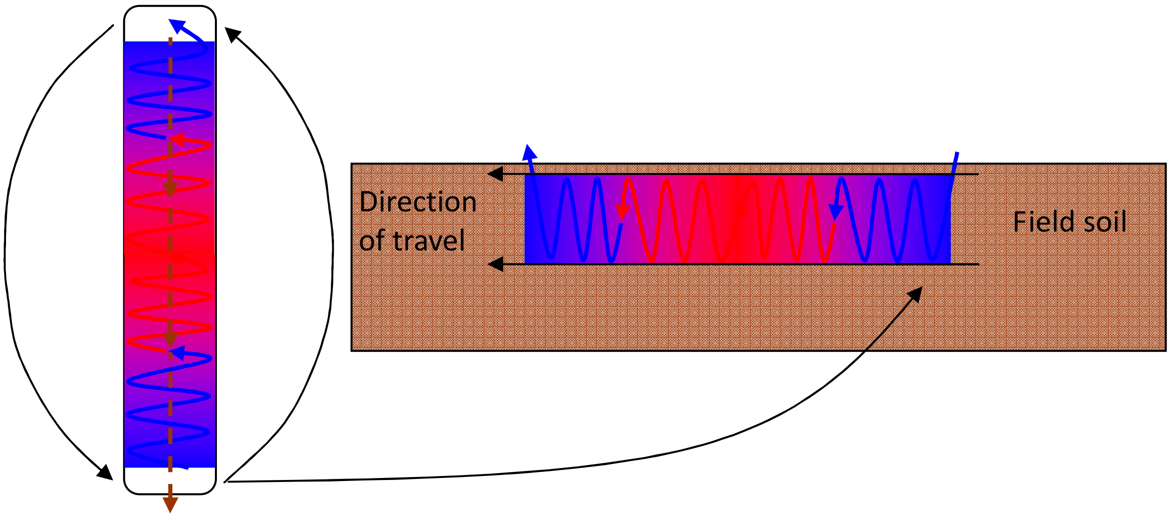



Figure 11. Conceptual rotation of the ex-situ two-stage, counter-flow, direct-contact, heat exchanger with soil flowing through a vertical vessel under gravity (from Figure 8) into an in-situ, horizontal position with the vessel moving through the soil and thus the soil moving through the vessel in the opposite direction.

#### 4.2.5.3. The inverted U tunnel design

An ISTW machine that travels through the soils is the general approach used by Danish ISTW researchers for both their prototype and final field band steaming machines (Figure 3). These use an inverted U shaped tunnel, with steam injection at the front and rotating tines to mix and move the soil, rather than just rely on passive movement of soil through the tunnel.

Figure 12. Danish design band steamer: left, prototype reprinted from (Kristensen *et al.*, 2005); right, field scale version of prototype band steamer (photo Hans Kjoeras).

The discussion so far may therefore appear to be a complicated way at arriving at the already known, but, the key differences with the concept in Figure 11 and the Danish design in Figure 3 is that the Danish design:

- uses a parallel-flow rather than a counter-flow heat exchange system;
- there is no heat recovery, instead the heat is left in the soil, and;
- steam is used as the heat transfer medium.

These are considerable differences which mean that the fundamentals of the two approaches are quite different, especially the thermodynamic exchanges, despite the apparent superficial similarities. The sequential analysis presented above, starting from first principles, gives this approach a sound theoretical underpinning, allowing alternative approaches to be ruled out at the theoretical level, leaving only viable approaches to translate into practical machines.

#### 4.2.5.4. The FFC, in-situ, two-stage, counter-flow, direct-contact, soil and air heat exchanger design

Combining the Danish tunnel approach and the in-situ, two-stage, counter-flow, direct-contact, heat exchanger produces the conceptual design shown in Figure 13, called the 'FFC (Future Farming Centre) design'.

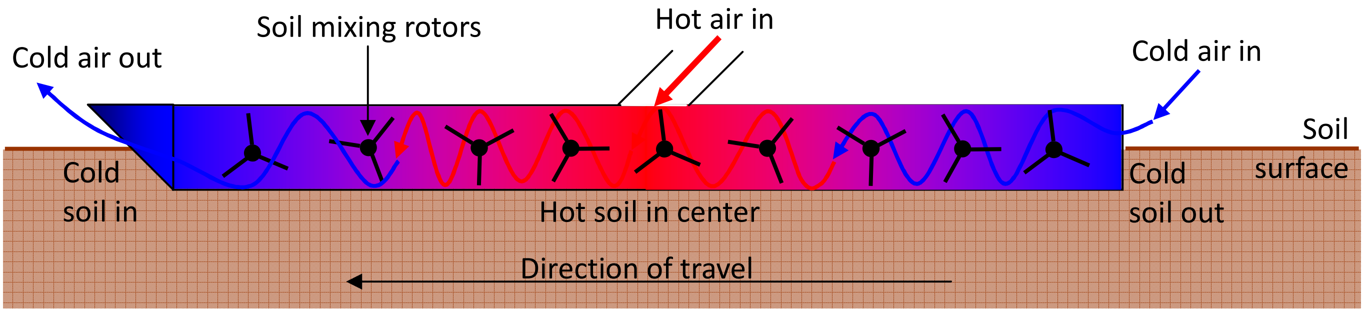



Figure 13. Conceptual design of an in-situ, two-stage (heating then cooling), counter-flow, direct-contact, soil and air heat exchanger using horizontal axis rotating tines for mixing: the 'FFC design'.

The features of the FFC design are:

- It is a fully in-situ design, i.e. soil remains in place, in the field.
- The inverted U shaped tunnel is very simple, and easy to fabricate, i.e. it is in keeping with the KISS principle.
- While the tunnel is open at the bottom, it is effectively sealed by the soil through which it is being drawn. The only openings to the atmosphere are at the front and back, and only the back needs to be sealed to prevent air escape as the air exit is at the front, thus ensuring as much of the heat as possible goes into the soil instead of non-target areas, e.g., the atmosphere.
- To assist the transfer of heat from air to soil a series of horizontal axis rotating tines 'mixing rotors' will be needed. These are conceptually the same as the baffles in the rotary dryer (page 43) except the cylinder has been cut into small sections which are then placed one after the other, i.e. this approach and the rotary dryer are fundamentally the same and therefore share the same fundamental abilities.
- The size, shape (design), number, speed of rotation, etc of the mixing rotors will be critical for effective operation, especially over widely varying soil types and conditions, including stony conditions. As noted on page 46 there is very extensive theoretical and practical knowledge to leverage to achieve this. Critical factors include:
    - The tine shape needs to ensure that all of the soil is effectively mixed with the airstream. It is envisenged that a tine with a shaft with a narrow cross-section facing the airstream with a short but wide 'shovel' a the end, is likely to best achieve this, such as the tines used on rotary spading machines and used on the Cultivit hot air pasteuriser (Figure 5) and the shovel will need to be angled for vertical entry into the soil and horizontal exit for maximum lifting effect while minimising longitudinal soil movement, also as on the Cultivit.
    - The tine shape will also be critical for minimising soil build-up on the tines themselves.
    - The speed of rotation will be important so that soil is effectively lifted rather than thrown into the airstream to minimise the energy used by the rotors while maximising heat transfer.
    - The minimum number of rotors should be used to minimise production and running costs.

    - The rotors should predominately aim to mix the soil with the air stream, rather than move it along the tunnel, so the machine can operate while stationary which will be important for start up / heating up.
- The potential for soil adhesion and build-up to the inside of the tunnel are minimised due to the soil and sides of the tunnel moving in parallel past each other.  The mixing rotors could also be designed to help clear any soil build-up that does occur inside the tunnel.
- The whole design is mechanically simple, therefore complying with the KISS principle.

### Critical FFC design issues to be addressed

There are, however, a number of critical factors and issues associated with this approach or that need detailed theoretical and/or empirical verification and/or engineering solutions.

- The fundamental issue with this design is that the temperature of the air from the heat recovery stage cannot be hotter than the maximum soil temperature, e.g., 90°C, due to thermodynamic laws, which mean that only the volume and pressure of the air can be manipulated to manage the amount of energy being transferred, and there are practical upper limits to these properties, i.e. too high a pressure would blow the soil out from under the tunnel, too large a volume would present issues with effective mixing of soil and air.
- The mid point where the heat enters the system and is mixed with the air containing the recovered heat is considered the critical design challenge of this system.  There are two general solutions to this:
    - To add small volumes of very hot air so to minimise the volume of extra air introduced;
    - To use the air from the heat recovery stage as the combustion air for the heat source.  This would require the air to be cleaned of soil particles, e.g., with a cyclone, prior to use, and the combustion process would still have to be tolerant to some residual levels of fine soil dust that get through the cleaning process.  The hot gas stream from this process would still have to go through a heat exchanger as discussed on page 35.
- While the parallel flow heat exchange process used in the Danish design is theoretically less efficient than a the counter-flow approach of the FFC design, it is practically simpler because the steam is drawn through the machine by the flow of soil while in the FFC, counter-flow design the air has to be forced (e.g., blown / pumped) against the soil flow.  This will require the vessel / tunnel to be well sealed against the soil to prevent losses, which in practice means the end of the tunnel where cold air is being injected, as the path of least resistance for the injected air is straight back out the end of the tunnel, rather than along the length of the tunnel.  Achieving a sufficiently airtight exit to the tunnel will require an elegant, i.e. simple, reliable and practical solution.  It is considered that a roller, possibly driven at ground speed, will give the best seal against the soil, with the rest of the roller being sealed to the tunnel by ‘scraper plates’ using materials such as PTFE.  NB this area will be at atmospheric temperatures so hot temperatures are not an issue.

The next requirements for the development of this system are thermodynamic calculations to determine the:

- general energy requirements for hot air ISTW across a range of soil types and moistures, both at theoretical (i.e. 100% efficiency) and practical levels (i.e. with real-world energy efficiencies);
- air, temperatures, pressures and volumes required by a FFC design ISTW system, including both heat recovery and heat injection.

These calculation will provide the constraints for the prototype designs, e.g., size of tunnels, wattage, etc., for an FFC design ISTW system.

# 5. Conclusions

The analysis of gas and particulate solid heat exchangers demonstrates the solid theoretical foundations on which a recycled hot air ISTW system is based. The design for the FFC, in-situ, two-stage, counter-flow, direct-contact, soil and air heat exchanger, highlights the key engineering issues that need to be solved to produced an efficient and effective hot-air ISTW system. However, considerable further research will still be required into a number of aspects of hot air ISTW to ensure it is fully feasible and to optimise the process.

# Section 3.
# Renewable fuel and energy use and efficiency

## 1. Summary

- Current ISTW designs consume a lot of fossil fuel / energy per hectare, which is unsustainable in the face of climate change. This report therefore determines which renewable fuels could be practical alternatives, and also considers the energy efficiency of different ISTW approaches to determine the key parameters.
- Among both biological and non-biological renewable fuels, vegetable oil and biogas (methane) are considered the best, but not exclusive options, because:
  - Agriculture (including forestry) is the almost exclusive producer of biological renewable fuels (biofuels) so using biofuels on farm has a number of practical and economic benefits.
  - Vegetable oil crops (rape, sunflower) are already established crops and processing the harvested seeds into oils is mechanically simple and requires low cost machines. Vegetable oil, as a liquid food product, is easy to handle and store, and can be used in burners designed for diesel with very minimal modifications.
  - Methane, produced by biodigesters, is an established farm biofuel in many parts of the world, so the technology is well understood. However, it requires more complex machinery than vegetable oil, and as methane is a gas, is highly combustible and also a greenhouse gas, it needs specialised handling and storage equipment, though this is widely available off the shelf as 'natural gas' is also methane. This means that burners and other equipment designed to use natural gas can be used for biogas with no, or minimal modification.
- Other biofuels, e.g. wood, straw, ethanol, are either less suited as a fuel in terms of their engineering requirements, or are less suited and/or less common for on farm production.
- Non-biological renewables, face the issue that their main output is electricity, which is completely impractical to use in large amounts, e.g. 100s or 1,000s of kilowatts on mobile agricultural equipment. The electricity would therefore have to be converted to an intermediary form, e.g. hydrogen, which brings a number of additional issues and problems that make it less attractive.
- Overall, among the two leading contenders of vegetable oil and biogas, it is considered that the main factor driving the choice of renewable fuel for ISTW will be which fuel the farm is best suited to produce, rather than ISTW engineering issues.
- Therefore using vegetable oil or methane as alternatives to fossil fuels is straightforward and inexpensive from an engineering perspective and these are well established biofuel crops so there are no technical impediments to the use of renewable fuels for ISTW.
- In terms of energy efficiency, the production of heat is the only energy transformation that is theoretically and practically 100% efficient. Therefore there are limited means of improving the efficiency of the process.
- The key areas where fuel and energy consumption can me minimised without compromising weed control are:
  - Reducing the volume of intrarow soil as much as practical, e.g. a reduction from a 7 x 7 cm to 5 x 5 cm intrarow area, reduces the diesel consumed from 808 to 412 $L \cdot ha^{-1}$ (the total amount depends on other parameters).
  - Recycling / recovering heat from the soil: at 20% heat recycling diesel use per ha is 866 $L \cdot ha^{-1}$ and at 80% recycling it is 216 $L \cdot ha^{-1}$ (depending on other parameters).
- To minimise the amount of fuel (of any type) used, minimising the intrarow soil volume and maximising the amount of heat recycled are the primary options.

# 2. Introduction

One of the key issues with current Intrarow soil thermal weeding (ISTW) is its large fuel consumption, e.g., $800 \cdot L \cdot ha^{-1}$ diesel (Melander & Kristensen, 2011), and current dependence on fossil fuels, such as diesel. With the multiple problems caused by fossil fuel use (Core Writing Team *et al.*, 2007), agriculture, along with the rest of society, needs to reduce and ideally eliminate fossil fuel use as rapidly as possible and move to renewable energy sources.

To address this issue a two-pronged approach is suggested:

- Replace fossil fuels with renewable fuels;
- Reduce the amount of energy used by ISTW.

Agriculture (including forestry) is the original source of biofuels as it is humanities main means of managing photosynthesis which directly captures energy from the sun. Farming is therefore well placed to produce and use renewable, fuels to use for ISTW, other thermal weeding approaches and farm energy supply in general.

The key approach to reduce fuel consumption / energy use in ISTW is to 'recycle' the heat from the treated soil as proposed in the previous sections of this report. Due to the high energy efficiency of heat production, i.e., close to theoretical limits, recycling heat is considered to be the only remaining thermal technique that is able to achieve significant energy savings. The other key variable for reducing energy use, is to minimise the volume of soil that is heated, both width and depth.

This report therefore considers the potential to use renewable fuels for ISTW and the energy and fuel consumption of a range of real-world ISTW scenarios using current steam based systems and recycled hot air systems.

# 3. Renewable fuels

Renewable fuels are those that are (mostly) derived directly or indirectly from the flow of energy from the sun. Direct use includes solar thermal and solar voltaic (electric) systems and indirect includes wind and hydro where the energy from the sun has been concentrated by the planet's weather systems. Biological fuels (biofuels) are indirectly derived from the sun's energy via plants, through photosynthesis. There is also a small amount of non-solar powered renewables such as tidal power, from the gravitational effect of the moon and geothermal, from the radioactive heat from the earth's center.

The energy captured from these different sources, can either be used directly at the point of use, e.g., electricity from solar voltaic or hydroelectricity to power lights, or the initial energy can be transformed into another 'second-stage' form, e.g., hydroelectricity can be used to electrolyse water into hydrogen fuel, and biological 'wastes' (e.g., manure, crop residues) can be 'digested' to produce biogas (methane). Typically these second-stage forms of renewables are gas or liquid fuels that aim to be direct replacements / substitutes for fossil fuels such as diesel and natural gas (methane).

## 3.1. On-farm renewables

Agriculture (including forestry) is the primary and nearly only source of photosynthetic material for civilisation. Farmers and growers are therefore the primary producers of biofuels. This is considered to give producers a significant advantage when it comes to accessing and using biofuels as they are both producer and consumer. However, the advantage of the different types of biofuels depends on a range of factors, including how complex the fuel is to grow and process, the nature of the farming operation, e.g., vegetables vs. livestock, as well as a range of economic factors, especially in countries with government subsidies for renewable energy.

Biofuels can also be divided into first and second stage fuel types. First stage fuels are materials that are burnt as harvested, for example, cereal straw and wood. Second-stage fuels are those that require some processing, and include, vegetable oil produced by crushing oil seeds (e.g. rape and sunflower), methane (biogas) produced by biodigesters, and ethanol produced by fermentation, e.g., of maize, followed by distillation. First stage fuels have the benefit of requiring little or no processing, e.g., straw can be burnt as bales straight from the field, while second stage fuels require processing equipment, some of it complex, so adding to capital costs.

Farms are also often well suited to non-biological renewable fuel production. For example, they often have open fields that are suited to wind turbines of a range of sizes, building roofs offer suitable sites for solar systems, and some have water courses that can be harnessed for hydroelectricity.

### 3.1.1. Initial renewables selection for ISTW

Of the many different types of renewables that could be used for ISTW a number can be eliminated as likely candidates on straightforward criteria.

Most of the output of non-biological renewables is electricity, which, while it is ideal for generating heat in a static situation, the requirement for cables, especially high voltage / amperage cables required to deliver the hundreds, even thousands of kilowatts required by ISTW machines in a field situation means electricity is not practical. To use non-biological renewables the electricity would have to be converted into an intermediate form, e.g., hydrogen via electrolysis. This would incur additional capital and running costs for the conversion and it would also incur energy loss during the conversion process further reducing the economics. Non-biologicals are therefore considered to have limited potential for ISTW unless producers already have systems installed on their farms or they can purchase them from third party suppliers.

First stage biofuels such as straw and wood, are also considered to have limited potential for several reasons.

- The bulky nature makes handling more difficult, but not impossible, as farms are often set up for handling bulky materials.
- More critically, solid fuels have a slow burn response time, i.e., it takes time for them to ignite and reach full heat output, and likewise, once burning, it is difficult to quickly and accurately increase or decrease their heat output. This is not such a problem in steam and water boiler systems where the water / steam acts as a thermal buffer and its flow and therefore heat delivery can be controlled, but for hot air systems which lack this buffering effect, it is considered highly problematic.
- Solid fuels, especially biofuels are not clean burning, as they produce ash and there is soot in the exhaust gas which can cause problems with heat exchangers.
- Most commonly available commercial / industrial boilers are not designed for burning solid biofuels so more specialised equipment, rather than off the shelf equipment, is required.

Solid fuels are therefore considered to have limited potential for hot air ISTW systems, unless fast-response burners are used and the farm is already setup for the production and use of bulky first-stage biofuels.

This then leaves second-stage biofuels, such as vegetable oil, ethanol and methane as the primary choice. The advantages of these are multiple.

- They have high energy density, i.e., a small volume / weight of fuel contains a large amount of energy so the weight and volume of fuel carried is minimised.
- The fuels vary from being very easy to handle to needing specialist equipment.

    - Vegetable oil is liquid at normal temperatures and pressures so can be stored in 'open' tanks and can be transferred by pouring and pumping with standard equipment.  It is non-toxic (it is edible), and does not readily combust, so it is very safe and simple to handle.
    - Liquid fuels such as ethanol are flammable and can be toxic, e.g., if entering waterways, inhaled, etc, so these require more complex handling and storage.
    - Gasses such as methane are (as the name indicates) a gas at atmospheric pressure, they are highly flammable, and methane is a green house gas, so they need specialised handling and storage equipment, which needs to meet safety and other regulations and have regular ongoing maintenance and certification, however, this equipment is commonly available off the shelf.
- The fuels are clean burning, with no ash and negligible soot production (unless the air mixture is to low), so they are the easiest to use.
- They can be burnt in existing burner and boiler designs, as these are mostly designed to run on diesel or methane (natural gas) so second-stage biofuels can be substituted for fossil fuels with little or no machinery modification.

### 3.1.2. Substitution requirements

The substitution requirements for the three main second-stage biofuels for fossil fuels are mostly straight forward.

A key advantage for the substitution is that the fuels are burnt in an external combustion engine, i.e., in a combustion chamber open to the atmosphere (even if the chamber is mostly enclosed).  This process is far more tolerant of variations in fuel type and specification, than internal combustion engines, especially modern highly technical engines that have very narrow fuel specifications.  In addition, in ISTW the heat production stage is separated from the heat application stage, which contrasts with other thermal weeding techniques, such as foliar thermal weeding, where the flames from the naturally aspirated burners are used directly on the plants.  In ISTW, both steam and hot air, fuel combustion takes place within a purpose designed, highly insulated refractory chamber, with forced aspiration, thus ensuring that the fuel is burnt in ideal conditions.  This provides much greater tolerance for variation in fuel types and properties, than could be used in internal combustion engines and foliar flamers.

A more important issue is likely to be whether the fuel handling system, e.g., pipes, pumps, tanks, etc., are able to handle the biofuel.  Somewhat counter-intuitively, materials such as vegetable oil, both refined and particularly raw, can corrode, soften, 'gum-up' and cause other harm to fuel systems designed for diesel.  Ethanol, methanol and similar materials can also corrode a range of materials, including aluminium and its alloys.  So while it may be straight forward to adapt the burner systems, e.g., converting a diesel burner to run on vegetable oil only requires a change of fuel atomising nozzle, more work may be required to ensure the entire fuel handling system, from tank to delivery is also compatible with the biofuel.  In general this is not difficult, e.g., changing the material used for pipes and using different pumps or pump linings.

For vegetable oils, both raw, refined, recycled (ex cooking oil) and biodiesel the only key change for the burners is to use fuel atomising nozzles rated for the fuels viscosity.  These are small items typically costing less than NZ$100.00, that are also wearing parts that need periodic replacement.  Minor, running changes such as fuel air mixtures, that are done as part of normal setup will also be required.  For recycled fuels, larger / finer filters may be needed if the oil is not sufficiently clean.

Natural gas and biogas are both methane, though with slightly different amounts and types of secondary compounds, e.g., sulphur compounds, so in most cases biogas can be directly substituted for natural gas in equipment without modification.  Equipment setup to use other gaseous hydrocarbon fuels, e.g., butane, propane, and mixtures of the two, LPG (liquefied petroleum gas), will need minor modifications e.g., nozzles and air:fuel mixtures, due to the slight differences in the gasses properties.

There are also duel-fuel burners on the market that can switch between diesel and methane while in use, so it would be straight forward to have burners that can swap between two of: diesel, vegetable oil, natural gas and biogas during operation.

Substituting ethanol for a fossil fuel is somewhat more complex as comparable fossil fuels, e.g., petrol / gasoline and naphtha, are not commonly used as fuels in heating boilers, due to their higher cost (though they are widely used in internal combustion engines, where ethanol is one of the main petrol substitutes). They are also highly flammable with flash points below standard atmospheric temperatures, making them inherently more dangerous, a further disincentive to using them as a fuel in external combustion engines where they are an explosion risk. Despite being uncommon, there are a range of burners and boilers designed to run on petrol and converting them to run on ethanol is straightforward, again, requiring changes to nozzles, air / fuel mixtures and ensuring that all fuel handling equipment is ethanol resistant.

### 3.1.2.1. Energy content of a range of fuels

Table 3 and Figure 14 shows the energy density by mass (mJ·kg$^{-1}$) and volume (mJ·L$^{-1}$) of a range of fuels.

Table 3. The mass and volume energy content of range of fossil and renewable fuels.

| Storage material | mJ·kg$^{-1}$ | mJ·L$^{-1}$ |
|---|---|---|
| **Fossil fuels** | | |
| Petrol | 44 | 34 |
| Diesel | 44 | 37 |
| Propane | 45 | 26 |
| Butane | 45 | 28 |
| Coal | 24 | 72 |
| **Renewables** | | |
| Hydrogen (at 70 MPa) | 123 | 5.6 |
| Methane (also fossil) liquid | 55 | 23 |
| Vegetable oil and animal fat | 38-40 | 37-40 |
| Ethanol | 25 | 24 |
| Plant matter (e.g., straw) | 10-16 | 1.6-17 |
| Wood | 16 | 2.5-22 |

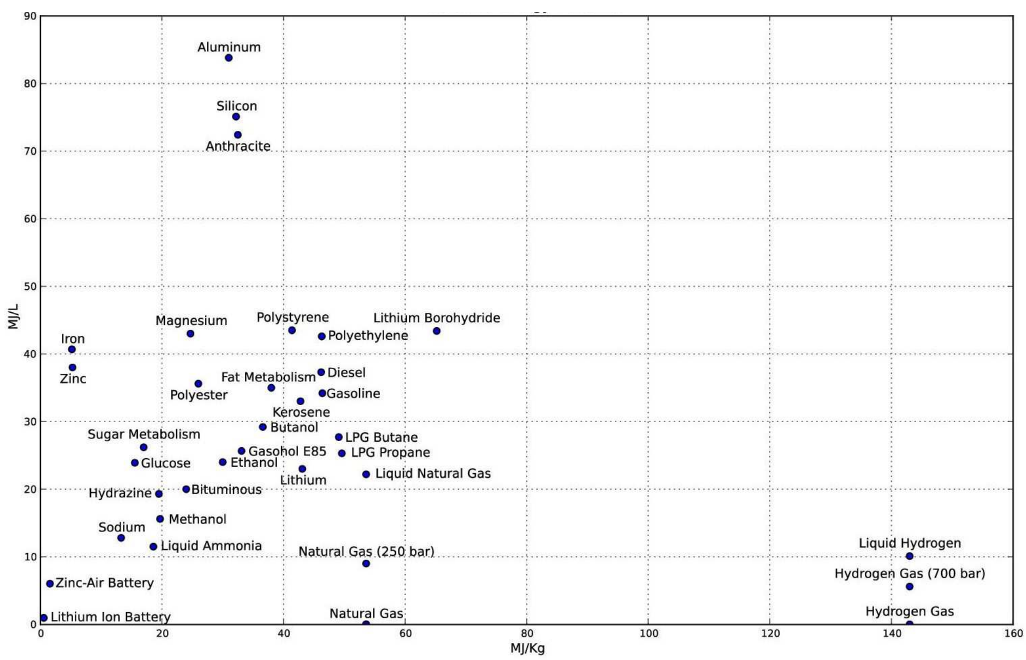



Figure 14. Plot of volume energy density (MJ·L$^{-1}$) against mass energy density (MJ·kg$^{-1}$) of a range of fuels (Wikipedia contributors, 2013b).

This highlights the relatively similar energy contents of easily substitutable renewables (e.g., vegetable oil for diesel) which minimises the technical barriers to adopting biofuels. Figure 14 in particular highlights the relationship between the volume vs. mass based energy densities ( $MJ \cdot L^{-1}$ vs. $MJ \cdot kg^{-1}$), which, depending on the situation, e.g., whether the volume or weight of fuel is more critical, can have important implications on fuel selection. E.g., hydrogen, has an extremely high energy density per kg, but as it is very light, its energy density per litre is very low, so large volumes are needed to provide the same amount energy as fuels with a far lower mass energy density, but higher volume energy density.

### 3.1.3. Choosing a second-stage biofuel for on-farm production

The decision which second-stage biofuel to use is therefore considered to be more dependent on each farms individual situation for biofuel production, rather than the engineering requirements of the ISTW equipment, as the former are more complex, they potentially require significant capital investment and changes to farm management while the engineering requirements are mostly inexpensive and straightforward. Factors affecting the decision are largely considered to hinge on whether the farm already produces biofuels, in which case, it is likely to be easiest and most cost effective to use the existing biofuel in ISTW machinery, even if it is not the cheapest option in terms of ISTW engineering / equipment and/or unit price of fuel, as the capital and other costs of setting up a second biofuel is likely to be high, making total costs more expensive.

If there is no current biofuel production, vegetable oil is the simplest option as oil seeds such as rape and sunflower are common crops and the only processing machinery required is a mechanical oil expeller press, which is simple and readily available. Processing rates can be very small, e.g., a few litres an hour as both seeds and final oil are easy to store, so the presses can be small, and therefore inexpensive. The downside of oil seeds is that the energy / hectare production is among the lowest of biofuel crops as only the seed component of the crop is used, not the whole biomass (though the straw and expeller cake can be used for other purposes, e.g., animal bedding and feed respectively). Also not all farms are equipped for oil seed production, e.g., vegetable farms, so they would have to also purchase the necessary farming machinery or contract crop production.

Biogas / methane production requires a biodigester, and while biodigesting is a highly scalable technology, with DIY type units that use 200 L plastic drums which produce a few tens of litres of gas, most commercially available plants in the developing world produce hundreds to thousands of kilowatts (megawatts) of methane, making them a significant capital investment. They also need a continual supply of digestible material, which ideally would be an existing ‘waste’ stream, such as animal manures from housed stock, vegetable processing waste, etc., Alternatively dedicated biodigester crops can be grown, e.g., sorghum, miscanthus, Jerusalem artichokes and pasture, although there will be financial issues to consider, e.g., loss of land from cash crop production, machinery requirements etc.. Wood is not suitable for biodigesting. Biodigesters also need ongoing management / supervision during operation due to safety issues. Setting up a biodigester solely to power ISTW equipment, is therefore, considered less likely to be economically viable, unless large areas of land are to be treated and there is an existing supply of ‘waste’ material to ferment, e.g., manures.

Ethanol production shares the same general issues as biogas production, in that a suitable source material(s) are needed, in this case fermentable sugars, and while the fermentation and distillation equipment are highly scalable, they are more expensive than a simple oil seed expeller press, and also require supervision during operation. Ethanol is considered to be most attractive where there is an existing ‘waste’ steam of readily fermentable product, e.g., whey using the “Carbery process”, or it can be purchased from commercial ethanol producers.

### 3.1.4. Renewable fuels for ISTW - conclusions

In summary, the most suitable renewable fuels for ISTW on farms are considered to be biogas (methane) and vegetable oil, due to the ability for farmers to produce their own, the ease of use (simple to substitute in terms of engineering), and both production capital and running costs. This is not to say that other renewable fuel (both biological and non-biological) options are impossible, but sourcing / producing them and/or complexity and cost of their production and increased complexity of fossil fuel substitution mean that in the absence of other compelling factors, e.g., an existing biofuel production infrastructure or local supply, the alternatives are less likely to make practical or economic sense.

Therefore the current use of fossil fuels for ISTW can be replaced by renewables, most likely produced on-farm. This is not to say that renewables are necessarily cheaper than fossil fuels, and as cost is often a major purchase factor for farm inputs such as fuel, farmers may decide to buy on price rather than issues such as the impact of their decision on climate change. However, as the price of fossil fuels forecast to rise and their availability to decrease, so although renewables are currently more expensive than fossil fuels, this is expected to reverse on a permanant basis, at which point the uptake of renewables will also be driven by price (Stern, 2007).

# 4. Energy use and efficiency

In most situations, using energy (e.g., burning fuel in an internal combustion engine) is less than 100% efficient due to the laws of thermodynamics, with the unused energy being lost as heat. The ratio between the useful energy output of a machine and the energy input, is called the energy conversion efficiency (η). Typical values for a range of machines are given in Table 4.

Table 4. Energy conversion efficiency examples (Wikipedia contributors, 2013a)

| Conversion process | Energy efficiency |
|---|---|
| Gas turbine electricity generation | up to 40% |
| Gas turbine plus steam turbine (combined cycle) electricity generation | up to 60% |
| Water turbine electricity generation | up to 90% (practically achieved) |
| Wind turbine electricity generation | up to 59% (theoretical limit) |
| Solar cell | 6–40% (technology dependent, 15% most often, 85–90% theoretical limit) |
| Fuel cell | up to 85% |
| Combustion engine | 10–50% |
| Electric motors | 70–99.99% (above 200W); 50–90% (between 10–200W); 30–60% (small ones < 10W) |
| Household refrigerators | low-end systems ~ 20%; high end systems ~ 40–50% |
| Incandescent light bulb | 0.7–5.1% |
| Light-emitting diode (LED) | 4–15% |
| Fluorescent lamps | 8–16% |
| Low-pressure sodium lamps | 15–29% |
| Metal halide lamps | 9–17% |
| Electrolysis of water | 50–70% (80–94% theoretical maximum) |

However, the only exception to energy conversion theoretically and practically being less than 100% is where the energy is converted to heat, because, as heat has the highest entropy of all forms of energy, energy conversion efficiency of 100% is theoretically and practically possible, i.e., all of the source energy (e.g., chemical fuel or electricity) is converted into heat energy and nothing else.

## 4.1. Finding energy savings in ISTW systems

As heat production is the aim of ISTW systems they can be 100% efficient in the conversion of chemical energy in the fuel into heat. The challenge for ISTW, is to ensure that all of the heat energy is delivered to the target and achieves useful work (killing weed seeds) without applying more heat than is needed, i.e., there is minimal 'loss' of heat from things such as the boiler, pipe work, etc. and that all the heat ends up in the intrarow soil, heating it just enough to kill the weed seeds. However, while it is possible to minimise heat loss to very small amounts, it is often not economically practical, as the cost of better insulation is much higher than the savings from reduced heat / energy loss. However, standard quality boiler insulation can reduce heat loss to a few percent. Standard steam boilers also loose heat via the chimney with the exhaust combustion gases. This low grade heat can be reclaimed with condensing boiler designs, however, like insulation, there are economic costs vs. returns in terms of the energy saved vs. the higher capital and maintenance cost of condensing boilers. Typical figures are an energy efficiency of 70%-80% for standard boilers and up to 98% for condensing boilers.

Hot air ISTW systems have the advantage over steam boilers in that all of the combustion gasses can either be directly used to heat the soil, or where concerns exist about possible toxicity, then a counterflow heat exchanger can be used to transfer the heat to 'clean' atmospheric air, a process with near to 100% efficiency (see also page 35).

The final area of energy loss is transfer of heat into the soil. Kristensen et al., (2005) measured the specific heat of two soil types (sand and clay) at two moisture levels (moist and dry) and then experimentally determined the efficiency of heat transfer by steam into the soil and found this ranged from 91% to 100% with the dry soils having higher efficiency, with the suggestion this was because they absorbed more of the steam. They went on to note, that once in the soil, the heat moved from the target band into the surrounding soil, which was effectively 'wasted' due to it not killing weeds in the target band. This is considered inevitable with any ISTW system that leaves the heat in the soil and the best solution to this is to recycle / reuse the heat. However this is not possible when using steam as the heat source, the solution is to use hot air and recycle the heat from the treated soil.

Using two counterflow heat exchangers (such as fluidised beds) in series, it is possible to use hot air to heat soil up and then use cool air to recover the heat, with close to 100% efficiency, due to the physics of counterflow heat exchangers, with losses mostly due to imperfect insulation (see also page 39). However, with the practical constraints of ISTW machinery operating in real-world farming, it will not be possible to achieve the theoretical efficiencies of these optimum systems, as, for example, there will be limits on how well the system can be insulated, especially the soil engaging parts.

It is not known how efficient the energy transfer into soils can be made in terms of both the general use of hot air for heat transfer with issues such as vaporising soil water, and the specifics, in terms of the possible machine designs, e.g., soil mixing rotors. Likewise the reverse process of recovering the heat from the soil faces the 'low grade heat issue', in that the air used to heat the soil will mostly likely be at higher temperatures e.g., 400°C and commensurately lower volumes, while the recovered air cannot exceed the final soil temperature, e.g., 120°C (due to thermodynamic laws) so it will have commensurately higher volume. There is likely to be some energy loss converting this cooler higher volume air stream into the higher temperature lower volume air needed to heat soil. (see also page 38).

To summarise, at a 'theoretical level' with 100% efficiency in heat recycling from the soil and back again it would be possible to treat a whole run of bed, with only the energy needed to heat the soil contained within the machine. In reality, the recycling process will not be 100% efficient, heat will be continually lost from the treatment area, e.g., through the steel components of the machinery, though the soil underneath the treatment tunnel and through the sides of the tunnel into the soil next to the treated strip. Such losses are complex to calculate, especially when different soil textures and moisture contents are taken into account, so the best way to determine these are experimentally using prototype designs.

Therefore, at this stage, the efficiencies of steam and recycled hot air ISTW systems can only be generally estimated. Despite these limitations they are still useful in indicating the potential of these systems and where the major losses occur and need to be addressed.

## 4.2. Energy use and efficiency calculations

Table 5 shows the energy calculations for ISTW systems. The first section calculates the volume of soil to be treated based on the intrarow width and depth, the number of rows per bed and bed width. The second section calculates the energy required per hectare to treat the above intrarow scenario and the increase in temperature of the soil to achieve weed seed death. The 1,430 kJ·m3·°C$^{-1}$ volumetric specific heat of soil is a ballpark figure derived from an average soil density of 1.3 g·cm$^{3}$ (tonne·m$^{3}$) and an average mass specific heat of soil of 1.1 kJ·kg·°C$^{-1}$. The third section converts the energy into litres of diesel. Diesel is used as it is the standard agricultural fuel, a measure of immediate meaning to farmers and growers and it can be converted to financial cost ha$^{-1}$ using current fuel prices. The fourth and final section, starting with the machine work rate, calculates the power (kW) of the boiler or energy source required (akin to the engine power of a tractor - the larger the number / bigger the engine the faster the machine can perform a given task).

Table 5. General theoretical energy and fuel calculations for ISTW.

| Value | Units | Item |
|---|---|---|
| 7 | cm | Intrarow width |
| 7 | cm | Intrarow depth |
| 0.0049 | m$^2$ | Intrarow cross section area meters |
| 1.8 | m | Bed width |
| 4 | count | Number of rows per bed |
| 22,222 | m | Length of intrarow per ha |
| 109 | m$^3$ | Volume of intrarow soil per ha |
| 10 | °C | Starting soil temperature |
| 100 | °C | Maximum soil temperature |
| 90 | °C | Increase in temperature to achieve |
| 1,430 | kJ·m3·°C$^{-1}$ | Mean volumetric specific heat of soil |
| 14,014,000 | kJ·ha$^{-1}$ | Energy required to treat 1 ha of field |
| 36,400 | kJ·L$^{-1}$ | Energy content of diesel |
| 808 | L·ha$^{-1}$ | Diesel use per hectare |
| 2 | km·h$^{-1}$ | Operating speed |
| 40,000 | seconds | Time to treat 1 ha in seconds, heating four rows / one bed |
| 1,401 | kW | Power required to heat four rows / one bed at a time |

The key variable, i.e., factor that can be altered and still achieve good weed control, in the above calculations is the intrarow dimensions. Table 6 is a sensitivity table that demonstrates that minimising the volume of soil heated is critical to minimise the amount of energy required and the power needed.

Table 6. Sensitivity analysis based on Table 5 of the energy, diesel and power to treat 1 ha of field depending on the intrarow size.

| Intrarow size h × w cm | Energy kJ | Diesel L | Power kW |
|---|---|---|---|
| 5 | 7,150,000 | 196 | 715 |
| 6 | 10,296,000 | 283 | 1,030 |
| 7 | 14,014,000 | 385 | 1,401 |
| 8 | 18,304,000 | 503 | 1,830 |

Work rate is considered an important parameter, as farmers and growers often need to complete large amounts of field work in small periods of time. However, power requirements rapidly increase with increasing work rates (Table 7). At 4 km·h$^{-1}$ nearly three megawatts is required per bed / 700 kW per row, which is a very substantial amount of heat to be directing at such small volume of soil. This is considered a clear indication of the engineering challenges of more effective ISTW systems.

Table 7. Sensitivity analysis based on Table 5 of the power requirements for different work rates.

| Work rate km·h$^{-1}$ | Power kW |
|---|---|
| 0.5 | 350 |
| 1.0 | 701 |
| 2.0 | 1,401 |
| 4.0 | 2,803 |

It should be noted that the amount of energy / fuel needed per hectare is not affected by the work rate / the amount of power, as power is a measure of energy consumption over time, rather than the total energy required per unit area.

Turning to comparisons of steam and recycled hot air. Table 8 shows estimated general efficiency calculations for the entire ISTW process for standard and condensing steam boilers and a recycled hot air system.

Table 8. Energy efficiency calculations for steam and recycled hot air ISTW systems, and the effect of efficiency on 'actual' energy, fuel and power based on the parameters in Table 5.

| | Steam boiler | Condensing steam boiler | Recycled hot air |
|---|---|---|---|
| Heat production efficiency inc. boiler insulation | 85% | 95% | 100% |
| Heat exchanger efficiency | 100% | 100% | 98% |
| Delivery efficiency | 97% | 97% | 97% |
| Soil transfer efficiency | 95% | 95% | 90% |
| **Total system delivery efficiency** | **78%** | **88%** | **86%** |
| Theoretical energy needed (kJ·ha$^{-1}$) (Table 5) | 14,014,000 | 14,014,000 | 14,014,000 |
| Actual energy needed (kJ·ha$^{-1}$) | 17,051,184 | 15,759,794 | 16,038,462 |
| Theoretical diesel required (L·ha$^{-1}$) (Table 5) | 385 | 385 | 385 |
| Actual diesel required (L·ha$^{-1}$) | 468 | 433 | 441 |
| Theoretical power required (kW) (Table 5) | 1,401 | 1,401 | 1,401 |
| Actual power required (kW) | 1,705 | 1,576 | 1,604 |
| Recycling efficiency | Not possible | Not possible | 50% |
| Actual energy required to treat 1 ha | | | 8,019,231 |
| Actual diesel required per ha | | | 220 |
| Actual power required (kW) | | | 802 |

Overall the condensing boiler and hot air systems have similar overall efficiency figures. The theoretical energy calculations in Table 5 when multiplied by the overall energy efficiency of the systems give the 'actual' energy and diesel fuel requirements can be calculated, i.e., the 'actual' real-world performance. The third section of Table 8 shows the energy, fuel and power requirements with hot air recycling at 50% of the heat in the soil recycled, with Table 9 showing a sensitivity analysis for energy, fuel and power across a range of soil heat recycling levels. This clearly demonstrates the benefits of maximising energy / heat recycling on both total energy required and the power needed.

Table 9. Sensitivity analysis based on Table 8 of the actual energy, diesel and power required for a range of energy recycling efficiencies.

| Recycling efficiency | 20% | 40% | 60% | 80% |
|---|---|---|---|---|
| Actual energy needed ($kJ \cdot ha^{-1}$) | 12,830,770 | 9,623,077 | 6,415,385 | 3,207,692 |
| Actual diesel required ($L \cdot ha^{-1}$) | 352 | 264 | 176 | 88 |
| Actual power required (kW) | 1,283 | 962 | 642 | 321 |

# 5. Conclusions

There are a number of well established renewable fuels that can be used as replacements for fossil fuels in ISTW machinery, with biogas (methane) and vegetable oil being the most likely, but not the only options. The choice of which renewable is preferable, is considered to be mostly dependent on fuel production issues, rather than ISTW engineering issues, at these are straightforward and inexpensive.

To minimise all fuel / energy use, the primary drivers are to reduce the volume (width and depth) of the intrarow soil to be treated to a minimum, and to maximise the efficiency of the heat recycling system.

If both fossil fuels and energy minimisation techniques can be optimised, then, ISTW has the potential to be both a highly effective intrarow weed management tool, while minimising fuel use and its impact on climate change.

# Section 4.
# Research experiments

## 1. Summary

- Intrarow soil thermal weeding (ISTW) is a technique for weed management / control based on killing the weed-seedbank 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 herbicide 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.
- The first section of this report 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, which resulted in 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.

# 2. Introduction

Intrarow soil thermal weeding (ISTW) is considered to still be in the early stages of development and there continue to be a issues that need to be resolved. In the previous sections of this report the key main / overarching issues of ISTW were identified 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 specific issues that need further research were identified as:

- 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:

1. The effect of treatment temperature × aggregate size × heat type on seed mortality and heating time;
2. The effect of treatment temperature × SMC on seed mortality and heating time;
3. 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.

## 2.1. Temperature and duration

As discussed on page 16 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.*, 2002b; Melander & Jørgensen, 2004).

Treatment duration, particularly the cooling down stage, in most experiments has not been controlled with the soil being left in situ until it has cooled to ambient.

In the heat recycling system proposed in this report 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.

## 2.2. 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 (see page 21). 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.

## 2.3. 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 (see page 29 and 35). 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.

## 2.4. 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 (see pages 18 and 21).

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.

### 2.4.1. 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 section 1 of this report (page 20) it was suggested 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 knows, (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 tern results in significant compaction, then it is 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 on page 47 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 on page 47.

# 3. Methods

## 3.1. Soil collection and preparation

### 3.1.1. 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 dried by placing it 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.

### 3.1.2. 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, and, 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.

## 3.2. Experimental apparatus

### 3.2.1. Steam and hot air supply

Steam was generated using a 60 L capacity, insulated, 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.

### 3.2.2. 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).

### 3.2.3. 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 join 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. A 30 mm ID hole was cut through the side of the pipe 20 mm from the blanked off end with the hose from a vacuum cleaner (Nilfisk Action Plus CLE) inserted into it, so it could suck or blow air out of or into the pipe. With the pipe standing on its base, 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. Sucking air through the sample also cooled it 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.

### 3.2.4. 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. The mean of the 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 electricity monitor.

## 3.3. General methods

### 3.3.1. 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 ((soil wet weight-soil dry weight)/soil dry weight)×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 10) and then confirmed, using the gravimetric method, during pre-experimental testing.

Table 10. The amount of water added (g) to each 400 g of soil to achieve the four target SMC (Table 11) 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 large soil 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.

### 3.3.2. 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.

## 3.4. Individual experimental design

### 3.4.1. 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.

### 3.4.2. 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) 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.

### 3.4.3. 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 11).

Table 11. 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 for five seconds. 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·cm$^2$ 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·cm$^2$ (own calculation) but less than a tractor at 1.0 kg·cm$^2$ (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 thick 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.

# 4. Results

## 4.1. 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.

## 4.2. 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 12.

Table 12. 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%.

## 4.3. Experimental results

### 4.3.1. 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 x 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 13 and Table 14.

Table 13. The effect of the interaction of aggregate size x 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.

| | Heat type | | |
|---|---|---|---|
| **Aggregate size** | **Air** | **Steam** | **Mean** |
| **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 14. 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 x temperature was significant p>0.001 as were the individual factors: SMC p=0.034 and temperature p>0.001 (Table 15).

Table 15. 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.

| | Temperature °C | | | | | |
|---|---|---|---|---|---|---|
| **SMC** | **60** | **70** | **80** | **90** | **100** | **Mean** |
| **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 × 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 16).

Table 16. 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.

| | Texture | | | |
|---|---|---|---|---|
| **SMC** | **Clay** | **Sand** | **Silt** | **Mean** |
| **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 | |

### 4.3.2. 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 × temperature p=0.987, heat type × temperature p=0.899 and aggregate size x heat type p=0.155. The individual factors were all significant at p<0.001, Table 17, Table 18 and Table 19.

Table 17. 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 18. 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 19. 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 × temperature and the individual factors were all significant p>0.001.

Table 20. 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.

| | Temperature °C | | | | | |
|---|---|---|---|---|---|---|
| **SMC** | **60** | **70** | **80** | **90** | **100** | **Mean** |
| **A** | 50.2 | 44.2 | 17.5 | 11.2 | 4.7 | 25.5 |
| **B** | 19.2 | 11.0 | 3.4 | 0.7 | 0.0 | 6.8 |
| **C** | 15.0 | 7.9 | 3.7 | 1.1 | 0.3 | 5.6 |
| **D** | 10.8 | 6.6 | 3.9 | 1.1 | 0.7 | 4.6 |
| **Mean** | 23.8 | 17.4 | 7.0 | 3.5 | 1.4 | |

### 4.3.3. Bulk density

In expt. 3, the effect on bulk density ($g \cdot cm^3$) was significant for the interaction of SMC × soil texture p=0.003 and the individual factors p>0.001 (Table 21).

Table 21. The effect of the interaction of soil texture × SMC on bulk density ($g \cdot cm^3$) 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.

| | | Texture | | |
|---|---|---|---|---|
| **SMC** | **Clay** | **Sand** | **Silt** | **Mean** |
| **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 | |

### 4.3.4. Crush weight

The effect on crushing weight (kg) was significant p<0.001 for the interaction and individual treatments (Table 22). The means for the individual factor are not shown as these are considered to be of no practical information.

Table 22. The amount of weight (kg) required to crush the dried soil cylinders, $LSD_{0.05}$ is 73.38.

| | Texture | | |
|---|---|---|---|
| **SMC** | **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 |

### 4.3.5. Final weights

The final weights of the soil cylinders after drying is presented in Table 23. These were not statistically analysed as they are not experimental results but are for methodological cross-checking .

Table 23. The final weight (g) of the soil cylinders after drying.

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

# 5. Discussion

## 5.1. 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. 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 fundamental thermodynamic and 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 could 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 scale of the effects being studied, that it is fit for purpose.

## 5.2. 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.

### 5.2.1. 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 an small increase in time at 90 and 100°C (Table 14 and Table 15). 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 condensed 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. 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.

### 5.2.2. Aggregate size

The effect of aggregate size on heating time also needs to be compared with thermodynamic predictions as well as among the results (Table 13). 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 increases, 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 $W \cdot m^{-1} \cdot K^{-1}$ 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 course soil heated up faster, although the differences were not large and only statistically significant at 60°C.

### 5.2.3. 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 13) 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 25) produces a confused picture.

Table 24. The percentage difference in heating times (seconds) between hot air and steam.

| | Heat type | | |
|---|---|---|---|
| **Aggregate size** | **Air** | **Steam** | **% difference** |
| **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.

### 5.2.4. 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 15 and Table 16). 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 25 shows the calculated energy required to heat the soils used in expt. 3, using a starting temperature for the soil of 20°C.

Table 25. The amount of theoretical /calculated energy (Mj) required to heat the three soil textures at the four SMC used plus dry soil.

| | Texture | | |
|---|---|---|---|
| **SMC** | **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 26 and Table 27.

Table 26. The theoretical percentage increase in energy required to heat the soils in Table 25 compared with dry soil.

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

Table 27. The actual percentage difference in heating time for the soils compared with SMC ‘A’

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

Table 28. The difference (in percentage points) between Table 26 and Table 27

| | Texture | | |
|---|---|---|---|
| **SMC** | **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 28. 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 observation 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, which may explain why it did no change from less to greater than theoretical heating times. This clearly needs more research to confirm.

The results for expt. 2 (Table 15) 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 15 is therefore equivalent to the silt column in Table 16 (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, but no explanation can be suggested.

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 29).

Table 29. Percentage increase in time taken to reach target temperatures of 'moist' and 'dry' soil for two soil textures, calculated from (Melander & Kristensen, 2011).

| | Temperature | | | |
|---|---|---|---|---|
| **Soil type** | **60°C** | **70°C** | **80°C** | **Mean** |
| Sandy loam | 4% | 9% | 2% | 5% |
| Sand | 31% | 25% | 16% | 24% |

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 on page 70 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 is considered important so the results reflect how the proposed field-machine designs would work.

## 5.3. 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.

The standard analytical / statistical approach to measuring weed survival, for both thermal weeding and herbicide research are dose-response curves, the technique being adopted for thermal weeding from herbicide research (Johan Ascard, Swedish Board of Agriculture, pers. comm.). However, in situations such as pre-crop emergence foliar thermal weeding and ISTW, the only outcome of interest to farmers and growers is 100% weed mortality, or better '120%' weed mortality, i.e., treatment parameters that includes a reasonable margin of error to 'guarantee' all weeds are killed. It is suggested that the use of dose-response curves moves the focus from 100% mortality, back to treatment parameters with lethal dose (LD) values at 50 and 95% mortality. Further it is suggested that one reason real-world ISTW is not achieving the 100% mortality desired by producers (Melander & Kristensen, 2011) may be that treatment temperature recommendations are based on LD90 and LD95 values, which would ensure <100% mortality is achieved. It is therefore suggested that a better experimental measurement is the one used by van Loenen et al., (2003), where success of soil heating was taken as 100% mortality in all replicates. This should then be treated as the minimum temperature required to ensure 100% mortality in ISTW on-farm, and that a 10% or 20% increase on this figure be used as a margin of error, e.g. as is typical of engineered structures. Therefore, for this research, seed mortality / seedling emergence figures have therefore been simply analysed by ANOVA, to determine if there are statistical differences or not, but the key measurement is if 100% seed death / zero weedlings has been achieved.

Unfortunately, on this measurement these results could be considered less than positive 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.

### 5.3.1. Temperature

The response to increasing temperature was generally linear for both expts. 1 and 2 (Table 17 and Table 20). 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.

Previous research on temperature has focused on identifying the maximum temperature required for effective weed seed death, e.g. (van Loenen *et al.*, 2003; Melander & Jørgensen, 2004; Melander & Kristensen, 2011). However, the results of these previous studies have produced conflicting results, as have these experiments.

van Loenen et al., (2003) used an “aerated steam” system (that is perhaps more accurately described as humidified hot air), where air was circulated through a heater (that determined the temperature), which then had hot water sprayed into it, with 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 on two soil textures, a sand and clay loam at 10.5% and 34.2% soil moisture, respectively. 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 14) 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.). Even at 100°C 100% seed mortality was not achieved, and there was a large difference in mortality between hot air and steam. 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 therefore range from approx. 18 to 74 s.

Among all the above research there is a wide range of ‘maximum’ temperatures at which 100% seed mortality is achieved, plus the ‘maximum’ also appears to vary with heat type. As this is clearly contradictory, it suggests that temperature alone is **not** the only treatment variable that determines seed death and that other factors must be playing a role.

Treatment duration is one of those factors considered to have a key role. This is because they vary widely among the experiments, 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 that the longer the soil and seeds are at the treatment temperature, the lower the maximum temperature required to achieve complete weed seed death and follows from the ‘five temperature zones’ theory described on page 16. 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 thermal time, also referred to as ‘growing degree days’ or ‘heat units’ that are 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 infection point of the temperature response curves, e.g., approx. 40°C, may be better able to 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.

### 5.3.2. 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 20), 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 20). 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 that 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 research is therefore required.

### 5.3.3. Heat type and the further role of water

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 19). 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 13) 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 20), 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 vaporise water in the soil as it is heated, which produces a 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, 1989a) 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.

### 5.3.4. 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 18). 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 issue could be managed are suggested, so it is clearly an area that also needs further research. At a practical farm level, however, the message is very clear that large aggregates will reduce the effectiveness of ISTW and that aggregate size should be reduced to the minimum consistent with good agronomic practice.

## 5.4. 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 of 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 comparatibility 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·cm$^3$ for sands and 1.1-1.6 g·cm$^3$ 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 21).

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 cm$^3$ and the soils ranged from 0.4 to 0.48 g·cm$^3$ 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.

## 5.5. 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 22). As hypothesized, sand does not form 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 and the importance of multidisciplinary input into ISTW research.

## 5.6. Final weights

The weight of the soil cylinders after drying are all below the 400 g starting weight (Table 23) 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 cylinders with higher SMCs. 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.

## 5.7. 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 also indicate 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 × 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, 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. However, heating ‘moist’ soil above 100°C faces the very significant barrier of the boiling point of water with its very large latent heat of evaporation, i.e., when the temperature of the soil reaches 100°C, the water it contains will start vaporising, which will have a very large cooling effect. Heating the soil in a saturated atmosphere may help reduce this issue but it cannot eliminate it. 100°C may therefore be a practical upper temperature limit, meaning that treatment duration is the only option left to ensure 100% seed mortality. That then means that determining if thermal-time gives better predictions of seed mortality than maximum temperature will be even more critical. 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 validate thermal-time models.

The results for soil moisture in this, other ISTW research and research into disinfesting 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 / weedling 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 $kg \cdot m^3$ 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 $water \cdot ha^{-1}$ (32 tonnes $water \cdot ha^{-1}$). These kinds of volumes are not practical to apply via mobile machinery only by 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, presumably 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 the aggregate problem 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 limitation, 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 apart from ensuring that ISTW machinery minimises soil compaction.

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 absorbtion 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.

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.

# General conclusions

Intrarow soil thermal weeding (ISTW) is considered to be a potentially vital herbicide replacement technology, due to its broad-spectrum nature (kills all therophyte weed seeds), long residual effect (for the life of the crop) and compatibility with all rowcrops.  However, the technology is still considered to be at the early development stages, with some significant issues, mainly high fossil fuel use, mechanical complexity and less than 100% weed seed mortality.

The solution proposed in this report, to use hot air as the heat transfer medium and to recycle heat from treated soil, is considered to have significant potential to address the quantity of fuel used and mechanical complexity, however, they are still at the conceptual stage and require prototyping and considerable further development.

The technical issue of fossil fuel use is considered to be solved as the standard farm biofuels of biogas (methane) and vegetable oil are mechanically easy to substitute for gas fuels (e.g. natural gas) and diesel.

The literature review and the experiments have highlighted the key variable parameters that affect the efficacy of ISTW, namely soil / seed moisture content, temperature × duration interaction (thermal time), and aggregate size.  However, these still require further work, potentially considerable, to fully 'iron out' which would ideally be done in conjunction with the hot air recycling ISTW prototypes to ensure its effectiveness.

It is hoped that this information will facilitate the transformation of ISTW from a potential, to an actual, farm-ready technology.

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# 7. References

Ascard, J. (1998). Comparison of flaming and infrared radiation techniques for thermal weed control. *Weed Research, 38*, 69-76.

Bàrberi, P., Moonen, A. C., Peruzzi, A., Fontanelli, M. & Raffaelli, M. (2009). Weed suppression by soil steaming in combination with activating compounds. *Weed Research, 49*(1), 55-66. http://dx.doi.org/10.1111/j.1365-3180.2008.00653.x

Bertram, A. (1994). Measurement of heat transfer in thermal weed control. *Acta Horticulturae, 372*, 187-194. http://www.actahort.org/books/372/372_22.htm

Bloemhard, C. M. J., Arts, M. W. M. F., Scheepens, P. C. & Elema, A. G. (1992). Thermal inactivation of weed seeds and tubers during drying of pig manure. *Netherlands Journal of Agricultural Science, 40*, 11-19.

Bradford, K. J. (1995). Water relations in seed germination. In J. Kigel & G. Galili (Eds.), *Seed development and germination* (pp. 351–396). New York: Marcel Dekker Inc.

Brady, N. C. & Weil, R. R. (2008). *The nature and properties of soil* (14th ed.). Upper Saddle River, New Jersey: Pearson Education Inc. http://wps.prenhall.com/chet_brady_natureandp_14/

Čėsna, J., Sirvydas, A. & Lazauskas, P. (1998). *Physical changes in the weed plant in thermal weed control.* Proceedings of the 3rd EWRS Workshop on Physical Weed Control, Wye College, UK, 21. http://www.ewrs.org/pwc/doc/1998_Wye.pdf

Core Writing Team, Pachauri, R. K. & Reisinger, A. (Eds.). (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: Intergovernmental Panel of Climate Change. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm

Davies, B., Finney, B. & Eagle, D. (2001). *Resource Management: Soil*. Tonbridge: Farming Press Books

Diprose, M. F. & Benson, F. A. (1984a). The effect of externally applied electrostatic fields, microwave radiation and electric currents on plants and other organisms, with special reference to weed control. *Botanical Review, 50*(2), 171-223. http://dx.doi.org/10.1007/BF02861092

Diprose, M. F. & Benson, F. A. (1984b). Electrical methods of killing plants. *Journal of Agricultural Engineering Research, 30*, 197-209. http://www.sciencedirect.com/science/article/pii/S0021863484800219

Eddington, A. S. (1928). *The nature of the physical world*. New York: The Macmillan Company

Elsgaard, L. (2010). Dynamics of mineral nitrogen, water-soluble carbon and potential nitrification in band-steamed arable soil. *Biology and Fertility of Soils, 46*(8), 883-889. http://rd.springer.com/article/10.1007/s00374-010-0486-4

Elsgaard, L., Jørgensen, M. H. & Elmholt, S. (2010). Effects of band-steaming on microbial activity and abundance in organic farming soil. *Agriculture, Ecosystems & Environment, 137*(3–4), 223-230. http://www.sciencedirect.com/science/article/pii/S0167880910000411

Fergedal, S. (1993). *Weed control by freezing with liquid nitrogen and carbon dioxide snow. A comparison between flaming and freezing.* Proceedings of the Communications of the fourth international conference IFOAM: Non chemical weed control, Dijon, 163-166.

Fox , B. (1996). Weed waster. *New Scientist, 149*(2023-30), 22.

Gay, P., Piccarolo, P., Ricauda Aimonino, D. & Tortia, C. (2010a). A high efficacy steam soil disinfestation system, part II: Design and testing. *Biosystems Engineering, 107*(3), 194-201. http://www.sciencedirect.com/science/article/pii/S153751101000156X

Gay, P., Piccarolo, P., Ricauda Aimonino, D. & Tortia, C. (2010b). A high efficiency steam soil disinfestation system, part I: Physical background and steam supply optimisation. *Biosystems Engineering, 107*(2), 74-85. http://www.sciencedirect.com/science/article/pii/S1537511010001406

Guinée, J. (Ed.). (2002). *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*: Springer

Gummerson, R. J. (1986). The effect of constant temperatures and osmotic potentials on the germination of sugar beet. *Journal of Experimental Botany, 37*(6), 729-741. http://jxb.oxfordjournals.org/content/37/6/729.abstract

Hansson, D. & Svensson, S.-E. (2007). *Steaming soil in narrow bands to control weeds in row crops.* Proceedings of the 7th EWRS Workshop on Physical and Cultural Weed Control, Salem, Germany, 137. http://www.ewrs.org/pwc/doc/2007_Salem.pdf

Hansson, D. & Svensson, S. E. (2004). *Steaming soil in narrow strips for intra-row weed control in sugar beet.* Proceedings of the 6th EWRS Workshop on Physical and Cultural Weed Control, Lillehammer, Norway, 152. http://www.ewrs.org/pwc/doc/2004_Lillehammer_Corrected.pdf

Harker, K. N., O'Donovan, J. T., Blackshaw, R. E., Beckie, H. J., Mallory-Smith, C. & Maxwell, B. D. (2012). Our View. *Weed Science, 60*(2), 143-144. http://dx.doi.org/10.1614/WS-D-11-00177.1

Heisel, T., Schou, J., Andreasen, C. & Christensen, S. (2002). Using laser to measure stem thickness and cut weed stems. *Weed Research, 42*(3), 242-248. http://www.blackwell-synergy.com/doi/abs/10.1046/j.1365-3180.2002.00282.x

Hillel, D. (1980). *Fundamentals of soil physics*. New York, USA: Academic Press Inc.

Johnson, A. T. (2006). *Biology for engineers*. Boca Raton, Florida, USA: CRC. http://www.bre.umd.edu/predbiol.htm

Jørgensen, M. H., Kristensen, J. K., Melander, B. & Kristensen, E. F. (2004). *Thermal band heating for intra-row weed control.* Proceedings of the Engineering the Future, International Conference on Agricultural Engineering, AgEng 2004 Leuven, Belgium, 287-295. http://orgprints.org/4807/

Juroszek, P., Berg, M., Lukashyk, P. & Köpke, U. (2002). *Thermal control of Vicia hirsuta and Vicia tetrasperma in winter cereals.* Proceedings of the 5th EWRS Workshop on Physical and Cultural Weed Control, Pisa, Italy, 244-252.

Kristensen, E. F., Jørgensen, M. H. & Kristensen, J. K. (2005). *Intra-row weed control by use of band steaming.* Proceedings of the Researching Sustainable Systems: Proceedings of the First Scientific Conference of the International Society of Organic Agriculture Research, Adelaide, Australiahttp://orgprints.org/10006/

Marshall, E. J. P. (2010). Weed Research reaches volume 50! Looking back and looking forward. *Weed Research, 50*(1), 1-4. http://dx.doi.org/10.1111/j.1365-3180.2009.00760.x

Mavrogianopoulos, G. N., Frangoudakis, A. & Pandelakis, J. (2000). Energy efficient soil disinfestation by microwaves. *Journal of Agricultural Engineering Research, 75*(2), 149-153. http://www.sciencedirect.com/science/article/pii/S0021863499904924

Melander, B., Heisel, T. & Jørgensen, M. H. (2002a). *Aspects of steaming the soil to reduce weed seedling emergence.* Proceedings of the 12th EWRS Symposium, 236-237. http://orgprints.org/1547/1/Abstract_NL1.pdf

Melander, B., Heisel, T. & Jørgensen, M. H. (2002b). *Band-steaming for intra-row weed control.* Proceedings of the 5th EWRS Workshop on Physical Weed Control, Pisa, Italy, 216-219. http://www.ewrs.org/pwc/doc/2002_Pisa.pdf

Melander, B. & Jørgensen, M. H. (2003). *Band steaming for intra-row weed control in direct-sown vegetables.* Proceedings of the European Weed Research Society working group "Weed Management Systems in Vegetable Crops", Skierniewice, Poland, 13-15. http://orgprints.org/1513/

Melander, B. & Jørgensen, M. H. (2004). Soil steaming to reduce intrarow weed seedling emergence. *Weed Research, 45*, 202-211. http://onlinelibrary.wiley.com/doi/10.1111/j.1365-3180.2005.00449.x/abstract

Melander, B., Jørgensen, M. H. & Elsgaard, L. (2004). *Recent results in the development of band steaming for intra-row weed control.* Proceedings of the 6th EWRS Workshop on Physical and Cultural Weed Control, Lillehammer, Norway, 154. http://www.ewrs.org/pwc/doc/2004_Lillehammer_Corrected.pdf

Melander, B. & Kristensen, J. K. (2011). Soil steaming effects on weed seedling emergence under the influence of soil type, soil moisture, soil structure and heat duration. *Annals of Applied Biology, 158*(2), 194-203. http://dx.doi.org/10.1111/j.1744-7348.2010.00453.x

Mendes, M. A. S., Lima, P., Fonseca, J. N. L. & Santos, M. F. (2001). Eradication of *Fusarium oxysporum* in alfalfa seeds by thermal and chemical treatments. *Fitopatologia Brasileira, 26*(2), 148-152.

Merfield, C. N. (2006). *Organic F1 hybrid carrot seed (Daucus carota L.) production: the effect of crop density on seed yield and quality, thermal weeding and fungal pathogen management.* Unpublished PhD Thesis, Lincoln University. http://www.merfield.com/research/phd/. http://www.merfield.com/research/phd/index.htm

Merfield, C. N., Hampton, J. G. & Wratten, S. D. (2009). A direct-fired steam weeder. *Weed Research, 49*, 553–556. http://onlinelibrary.wiley.com/doi/10.1111/j.1365-3180.2009.00733.x/full

Mulder, D. (Ed.). (1979). *Soil disinfestation*. New York: Elsevier Scientific

Parish, S. (1989a). *Investigations into thermal techniques for weed control.* Proceedings of the Agricultural engineering Proceedings of the 11th international congress on agricultural engineering, 2151 2156.

Parish, S. (1989b). Weed control - testing the effects of infrared radiation. *Agricultural Engineer, 44*(2), 53-55.

Peruzzi, A., Frasconi, C., Martelloni, L., Fontanelli, M. & Raffaelli, M. (2012a). *Use of steam and exothermic compounds for weed seed-bank control in bands (band steaming).* Proceedings of the CIGR-Ageng 2012 International Conference on Agricultural Engineering, Valencia, Spain, 1-3. http://cigr.ageng2012.org/images/fotosg/tabla_137_C1852.pdf

Peruzzi, A., Raffaelli, M., Frasconi, C., Fontanelli, M. & Bàrberi, P. (2012b). Influence of an injection system on the effect of activated soil steaming on *Brassica juncea* and the natural weed seedbank. *Weed Research, 52*(2), 140-152. http://dx.doi.org/10.1111/j.1365-3180.2011.00901.x

Rifai, M. N., Miller, J., Gaduš, J., Otepka, P. & Košik, L. (2003a). Comparison of infrared, flame and steam units for their use in plant protection. *Research in Agricultural Engineering, 49*(2), 65-73.

Rifai, N. M., Miller, J., Gadus, J., Otepka, P. & Kosik, L. (2003b). Comparison of infrared, flame and steam units for their use in plant protection. *Research in Agricultural Engineering, 49*(2), 65-73.

Roberts, H. A. (Ed.). (1982). *Weed Control Handbook* (7th ed.). Oxford: Blackwell Scientific Publications

Runia, W. T. & Greenberger, A. (2004). *Dutch approach on alternatives to methyl bromide including a new development: hot air treatment.* Proceedings of the Proceeding of International conference on alternatives to methyl bromide, Lisbon, Portugalhttp://www.actahort.org/books/698/698_33.htm

Runia, W. T. & Greenberger, A. (2005). Preliminary results of physical soil disinfestation by hot air. *Acta Horticulturae, 698*, 251-256. http://www.actahort.org/books/698/698_33.htm

Runia, W. T., Molendijk, L. P., Neophytou, G. & Greenberger, A. (2006). Soil treatment with hot air (Cultivit) as alternative to methyl bromide. *Communications in agricultural and applied biological sciences, 71*(2 Pt A), 185-192. http://pubget.com/paper/17390791

Runia, W. T. & Molendijk, L. P. G. (2010). Physical methods for soil disinfestation in intensive agriculture: old methods and new approaches. *Acta Horticulturae, 883*, 249-258. http://www.actahort.org/books/883/883_31.htm

Sartorato, I., Zanin, G., Baldoin, C. & Zanche, C. (2006). Observations on the potential of microwaves for weed control. *Weed Research, 46*(1), 1-9. http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-3180.2006.00484.x

Sirvydas, A., Lazauskas, P., Vasinauskiene, R. & Kerpauskas, P. (2002). *Thermal weed control by water steam.* Proceedings of the 5th EWRS Workshop on Physical and Cultural Weed Control, Pisa, Italy, 253-262. http://www.ewrs.org/pwc/doc/2002_Pisa.pdf

Stern, N. (2007). *The Economics of Climate Change*. Cambridge: Cambridge University Press. http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm

Tenente, R. C. V., Gonzaga, V., Pinheiro, F. P., Tarchetti, P. & Rodrigues, V. (1999). Techniques to eradicate plant parasitic nematodes from infested maize, oat and rice seeds. *Nematropica, 29*(1), 17-24.

van Loenen, M. C. A., Turbett, Y., Mullins, C. E., Feilden, N. E. H., Wilson, M. J., Leifert, C. & Seel, W. E. (2003). Low temperature–short duration steaming of soil kills soil-borne pathogens, nematode pests and weeds. *European Journal of Plant Pathology, 109*(9), 993-1002. http://dx.doi.org/10.1023/B%3AEJPP.0000003830.49949.34

Vela-Múzquiz, R. (1984). Control of field weeds by microwave radiation. *Acta Horticulturae, 152*, 201-208. http://www.actahort.org/books/152/152_21.htm

Vigneault, C., Benoit, D. L. & McLaughlin, N. B. (1990). Energy aspects of weed electrocution. *Reviews of Weed Science, 5*, 15-26.

Wikipedia contributors. (2012). *KISS principle*. Retrieved 28 October 2012, 2012, http://en.wikipedia.org/w/index.php?title=KISS_principle&oldid=518403234

Wikipedia contributors. (2013a). *Energy conversion efficiency* Retrieved 19 May, 2013, http://en.wikipedia.org/w/index.php?title=Energy_conversion_efficiency&oldid=549798317

Wikipedia contributors. (2013b). *Energy density*. Retrieved 21 May, 2013, http://en.wikipedia.org/w/index.php?title=Energy_density&oldid=555996479

Zanche, C., de Baldoin, C., Amista, F., Giubbolini, L. & Beria, S. (2003). Design, construction and preliminary tests of a microwave prototype for weed control. *Rivista di Ingegneria Agraria, 34*(2), 31-38.