Intrarow soil thermal weeding research report: The effect of soil texture and moisture content on soil structure after mixing and heating with steam

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2. Summary

- Most of the current steam based, intrarow soil thermal weeding (ISTW) has been undertaken on sandy soils that do not form clods / highly compacted soil.
- In comparison, silt and clay soils do form clods / highly compacted soil, especially when the soils approach field capacity / are in a plastic state, and such damage is well known to cause significant, even dramatic reductions in crop / plant growth, such that avoiding compaction is a key aspect of these soils' management.
- Therefore, to be more widely used, ISTW systems need to be able to work on silt and clay soils without forming such compaction / clods.
- This experiment was designed to demonstrate the significant differences between sand, and silt and clay soils, over a range of soil moisture contents (SMC), in terms of their resistance (sand) and susceptibility (silt and clay) to compaction, to:
  - highlight the issue;
  - gain a better understanding of at which SMCs compaction becomes significant; and
  - highlight that ISTW systems need to be able to work on such soils without causing damage.
- The experiment compared the effects of heating soils to 100°C using steam, simulating moderate tillage, and moderate compaction, on three soil textures (sand, silt and clay), across a range of SMC from dry to field capacity, in a two factorial design.
- The sand soil was unaffected by the treatment at any SMC in practical agronomic terms. The clay and silt soils became highly compacted at higher SMCs, to the point that it was considered that crop growth would be very significantly curtailed.
- The experiment is considered to have unambiguously shown clear differences between the sand, and the silt and clay soils, and therefore that their susceptibility to compaction at higher SMC must be taken into account in the design and use of ISTW equipment.

3. Introduction

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

In the first report in this series, (Merfield, 2012a) it was claimed that different soil textures, e.g., sand, silt, and clays, would respond differently to ISTW in terms of the effects on soil structure and that soil moisture content (SMC) would interact with texture, e.g., sand soils have a similar response to ISTW treatment regardless of SMC while silts and clays may respond quite differently depending on SMC. The key concern is that the ISTW process of steam heating while mechanically mixing soils, especially at higher moisture contents, could result in silt and clay soils becoming so severely compacted that there would be significant negative impacts on crop growth (the effects of compaction on plant growth being well 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 in (Merfield, 2012b) would require a good gas seal at the rear of the treatment tunnels to ensure that the cold air being forced into the tunnel at that point, does not simply blow back out of the rear of the tunnel, rather than travelling up the tunnel, against the soil flow. One of the options to achieve a sufficiently good gas seal against both the sides and top of the tunnel, and more critically, against the soil, would be a small roller. Such a roller would have to exert sufficient downwards pressure to create an effective seal against the soil, which will have a compacting effect. The design of this experiment aims to simulate the mixing of the soil by the multiple tillage rotors of the Danish ISTW machine (Kristensen *et al.*, 2005) and the rear tunnel roller of the counter-flow hot air ISTW machine proposed in (Merfield, 2012b).

4. Methods

Hypothesis 1: That the different soil texture classes will respond differently to simulated ISTW treatment, in terms of the effect on soil structure measured by bulk density and the weight required to crush the soil post treatment. Sand is expected to be affected only minimally by ISTW treatment, while silt and clay soils will become compacted / form clods.

Hypothesis 2: That SMC will affect the three soil texture classes differently in terms of the effect on soil structure measured by bulk density and the weight required to crush the soil, i.e., there will be an interaction of soil texture and SMC. Again, sand will be minimally affected while silt and clay will become highly compacted at high SMC.

Hypothesis 3: That increasing the soil moisture content will increase the time taken to heat the soils to the target temperature because the additional water needs energy to heat it up.

4.1. Soil sources

Three soils, a sand, silt and clay that were considered to be typical 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, from under mixed cropping, it is described as a Templeton silty loam. The clay was collected from the farm of Bruce Gill, Doyleston, 43°45'15.23" S 172°19'59.32" E, from long term pasture under cattle, and is described as Ayreburn clay. The above GPS / Google earth locations are the exact sampling points to within five meters.

The soils were pushed through 6.35 mm sieve after collection and then placed approx. 4 cm deep in large plastic trays in a glasshouse to air dry for three weeks. They were then placed in 20 L air tight containers for storage until the start of the experiment.

4.2. Experimental apparatus

4.2.1. Steam supply

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

4.2.2. Retort and insulated drum

A heating retort was constructed from steel, consisting of a pipe 155 mm internal diameter (ID) 300 mm high, with the bottom end blanked off. Halfway up the pipe was a 5 mm thick baffle plate with one hundred 5 mm dia. holes, equidistantly spaced. A 32 mm ID pipe 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: the 'inlet pipe' which was connected to the hot water cylinder. A 10 mm ID pipe 1,000 mm long was connected to the opposite side of the retort from the inlet pipe at the bottom: the 'drain pipe' 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 was such that all the steam (gas) flow exited through the top of the retort and the soil being treated, and not through the drain pipe, which only vented liquid water. The design aim of the retort was to ensure an even and steady flow of steam through the soil being treated.

The retort was then placed inside a steel drum, 380 mm dia. and 400 mm tall, 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 steam generated would pass through the soil.

Prior to use, the retort was allowed to run at full steam output for 20 min, to ensure that all the apparatus was at a constant temperature, i.e., to fully heat up. This was verified by a constant temperature reading from the infrared thermometer (see below).

4.2.3. Treatment equipment

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

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

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.

The soil compression pipes were made of 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 plastic plunger that fitted snugly into the compression pipes, was filled with cement and the end painted to minimise soil adhesion.

4.2.4. Measurement equipment and calibration

The temperature of the soil during treatment was measured using a Mastech MS6530 infrared thermometer mounted on a camera tripod with the thermometer placed approx. 60 cm from the soil surface. Due to infrared emissivity varying among different materials, the infrared thermometer was calibrated using an RS 206-3722 digital thermometer using an RS 342-8899 type ‘K’ general purpose probe, by heating 500 g of dry silt soil to 140°C, then placing it in an aluminium tray, placing the digital thermometer probe on the soil surface and simultaneously taking the temperature of the soil next to the probe with the infrared thermometer placed 60 cm from the soil surface. Temperature readings were taken from the infrared thermometer for every 10°C between 130 and 40°C as measured by the probe thermometer. This was repeated three times (three replicates). The mean of three sets of readings provided the emissivity calibration.

The electrical power consumed by the hot water cylinder was measured using an Owl® CM119 OWL electricity monitor (2 Save Energy Ltd., www.theowl.com).

4.3. Experimental design

The experimental design had two factors: (1) soil texture, and (2) SMC, with three soil textures, sand, silt and clay (described above) and four SMC Table 1, with four replicates giving a total of 60 samples.

Table 1. 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%

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 equal 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.

For each soil texture, a sample was taken from five different depths within the 20 L storage containers and the SMC determined using the gravimetric method (Brady & Weil, 2008) with percentage SMC calculated as ((soil wet weight - soil dry weight)/soil dry weight)×100. The amount of water that needed to be added to each soil to bring it up to the four target SMC was calculated and then confirmed for correctness, using the gravimetric method, during pre-experimental testing Table 2.

Table 2. The amount of water added (g) to each 400 g of soil to achieve the four target SMC (Table 1) for each texture.

	Sand	**Silt**	**Clay**
A	17.2	10.5	1.5
B	37	30	61
C	77	70	121
D	117	110	181

The soils were then divided into 400 g samples and placed in 20 x 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. The bags were then left for 24 hours for the water and soil to equilibrate. Immediately prior to treatment, the soils were again briefly tumbled within the bags to break up any lumps that had formed.

4.3.1.1. Treatment

The soils were treated 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 of 100°C had been reached (i.e., 100°C was the actual temperature of the soil, not the calibrated reading). A manual stopwatch was used to record the duration of heating.

Immediately post heating the soil was transferred from the basket to the mixing pipe. It was then mixed with the paint mixer with the drill rotating anticlockwise, at about 100 rpm for five seconds with the paint mixer moved up and down five times. 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 soil was then transferred to a compression pipe, which was itself placed in a plastic container. 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 this gives a force of 0.45 $kg{\cdot}cm^2$ of soil surface. This weight was selected as the kind of compressive factor that might be imposed by ISTW machinery, being greater than exerted by a human e.g., 0.12 $kg{\cdot}cm^2$ (own calculation) but less than a tractor at 1.0 $kg{\cdot}cm^2$ (Davies *et al.*, 2001).

In addition there was an 'untreated' control of soil that had not been heated or mixed and that was only compressed in the pipes by the 1 kg plunger, not the additional 19 kg weight.

Care was taken to ensure that as little soil was left in the treatment basket and mixing pipe, particularly for the clay and silt textures at the higher SMCs as these strongly adhered to the equipment. A mixture of brushes, scrapers and compressed air were required to thoroughly remove the soil.

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 400 g of each soil texture from the intial SMC determined gravimetrically and dividing the dry weight by the volume.

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

Except for the experimental setup results, results were analysed by ANOVA.

5. Results

5.1. Experimental setup

The power consumed by the hot water cylinder was a constant 2.8 kw.

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

Table 3. Emissivity calibration for the infrared thermometer.

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

The SMC of the three soil textures after air drying, i.e., before additional water was added were: Sand 0.71%, Silt 2.38% and Clay 4.61%.

5.2. Experimental results

5.2.1. Heating time

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 4).

Table 4. Heating time for the interaction of soil texture and soil moisture content, with the means of the individual treatments (SMC and Texture). $LSD_{0.05}$ for the interaction 8.35 (main part of table), SMC 4.82 and texture 4.18 (mean column and row).

	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	

5.2.2. Bulk density

The effect on bulk density ($g{\cdot}cm^3$) was significant for the interaction of SMC and soil texture p=0.003 and the individual treatments p>0.001 (Table 5). The mean of SMC is not shown as this result is of limited practical information.

Table 5. The effect of heating, mixing and compressing three soil textures at four moisture contents on bulk density ($g \cdot cm^3$) and an untreated control (U). $LSD_{0.05}$ for the interaction is 0.0215 (main part of table), texture 0.0616 (mean row).

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

5.2.3. Crush weight

The effect on crushing weight (kg) was significant at $p<0.001$ for the interaction and individual treatments (Table 6). The individual means are not shown as these are considered to be of limited practical information.

Table 6. 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

5.2.4. Final weights

The final weights of the soil cylinders after drying is presented in Table 7.

Table 7. 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

6. Discussion

6.1. Experimental setup

The heating apparatus design is considered to be basic but sufficient for the purposes of this research.

For example, there are a number of factors which mean that it is not possible to accurately determine a number of physical parameters, for example. The 2.8 kw used by the steam generator is the amount of power consumed, not the actual energy in the form of steam passing through the soil samples. Even though the hot water cylinder and retort were insulated, there are inevitable heat losses though the apparatus, so the amount of energy passing through the soil will be lower. However, these losses are considered likely to be small, e.g., less than 0.1 kw, so they only represent a small percentage of the total energy flowing through the system. At the same time the steam flow was constant, so each sample will of received the same amount of steam.

In addition, not all of the available energy in the steam was transferred to the soil sample, i.e., some heat escaped unused, which was simply determined by that fact that it could be felt when manually placing and removing the basket from the retort. While such a basic setup is of no use for determining the precise physics of the process, the main factors of interest in this and related experiments are biological, e.g., seed mortality, or soil structure (which affects biology / plant growth), which have much larger inherent variability. Therefore, the imprecision of the equipment and method is considered to be sufficiently small in relation to variability of the parameters being measured, so that statistically valid and biologically significant results can be obtained.

Further, it must be noted the retort heating system is quite different to the enclosed heat transfer systems, such as fluidised bed heat exchanges and the proposed hot air ISTW system described in (Merfield, 2012a) and (Merfield, 2012b). The retort is a batch, single flow (the steam) heat exchanger, in contrast with the continual, counter-flow heat exchangers described in the previous two reports. It is not therefore possible to compare the thermodynamics of the two systems. This lack of comparability is not considered problematic, as the primary aim of the retort system is to undertake initial investigations of the biological effects of heating, for which the retort is considered a suitable surrogate for continual counter-flow exchange systems, and it is much simpler and cheaper.

A key limitation of the open retort is that wet soil samples cannot be heated with hot air, because heating is slowed dramatically due to the evaporation of the soil water into steam, which would be minimised in a closed system.

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

6.2. Heating time

The recording of heating time is to some extent, incidental to the primary objecting of the effects of the treatments on soil structure. It should be taken only as a guide to the effect of heating as there are many unknown variables, e.g., the amount of heat in the steam being absorbed by the soil and the effects of SMC on soil aggregate sizes, which other concurrent ISTW experiments have show to have a significant effect on heating time, as has the only other published research on the effect (Melander & Jørgensen, 2004).

The effect of increasing soil moisture on heating times is generally consistent with theory as the additional water requires energy to heat it so therefore soils with higher moisture contents take longer to heat up (Table 4).

For clay and silt the response is approximately linear, which is expected as the SMC were also linear. However, the highest SMC (D) for sand appears to be anomalous as it is double the previous SMC level (C) while there was little change at previous levels. The raw data for sand at SMC D is, 101, 110, 107 and 102 seconds, which have a standard deviation of 4.24, which indicates strong consistency among the four replicates, and therefore that the effect is likely to be real. Anecdotal observations during treatment, was that the SMC D sand treatment appeared to become fully saturated by water as heating progressed, 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. This clearly needs more research to confirm.

If the anomalous result for SMC D for sand is ignored, both silt and sand showed similar responses, which as they had similar weight of water added to them to achieve each of the target SMC, it indicates that they both responded similarly. As the clay soil had a higher field capacity, so more water had to be added to it to achieve the target SMC, it has a higher mass and should therefore take longer to heat up. Its results are therefore not directly comparable to silt and sand.

While the results are generally consistent with theory, looking in more detail the picture is more complex. 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 so with an initial soil temperature of approx. 25°C (which is taken as a given for the following example) the amount of energy for the soil to reach 100°C is 36.0 Mj. Water has a specific heat of 4.18 Mj·kg·°K so for the maximum amount of water added to the silt (110 g) 34.5 Mj is required to heat it up, which is close to the energy required to heat the dry soil, i.e., twice the amount of energy is required, so heating time should double. Table 8 shows the theoretical (calculated) energy required, based on the above assumptions, to heat the soils up.

Table 8. 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	36	36	36
A	41	39	36
B	48	45	55
C	60	58	74
D	73	70	93

To compare heating times with the theoretical energy required, which are different quantities, the percentage increase can be used, Table 9 and Table 10.

Table 9. The theoretical percentage increase in energy required to heat the soils in Table 8 compared with dry soil.

		Texture	
SMC	**Clay**	**Sand**	**Silt**
A	14%	8%	0%
B	33%	25%	53%
C	67%	61%	106%
D	103%	94%	158%

Table 10. The actual percentage increase 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 11. The difference between Table 9 and Table 10

		Texture	
SMC	**Clay**	**Sand**	**Silt**
A	n/a	n/a	n/a
B	8	-26	-47
C	-19	-49	-87
D	101	69	-144

While heating time is generally in agreement with theory (i.e., higher SMC take longer to heat) there are some significant variations among the details Table 11. For clay, at lower SMC, the difference between theory and experiment is small, but diverges at SMC 'D'. Sand has a larger variance including swapping from negative to positive, which is due to the disproportionally long heating time at SMC 'D' which may be due to the sand becoming a colloid hydrogel as discussed above. Silt in comparison required little extra heating time as SMC increased (Table 10) in increasing disparity from the theoretical calculations.

It therefore appears that the heating process is considerably more complex than the basic theoretical calculations assume. The different textures may well interact and absorb heat from the steam differently due to multiple factors, e.g., how the steam flow interacts with the different particle and aggregate sizes. A concurrent experiment studying the effects of aggregate size on heating has found significantly reduced heating times for larger aggregates, which it is presumed because the soil in the center of the aggregates is not being heated fully. Anecdotal visual observations of the soils at different SMCs is that the wetter clay and silt soils tend to form lumps / larger aggregates, which may be affecting heating times, though there may well be other factors contributing to the effect.

There has been little previous research into the effect of SMC in ISTW. Only one paper, Melander & Jørgensen (2004) has been found that empirically studied the effect of SMC on heating. However, the soils were both sands and they only described the SMC as dry and moist, without giving an quantitative measurement. The dry soils were quicker to heat up than the moist soils and there was a difference of the effect of moisture between the two soil textures even though they were both sands (Table 12).

Table 12. Percentage increase in time taken to reach target temperatures of a moist compared with dry soil for two soil textures. Calculated from (Melander & Jørgensen, 2004).

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

Despite both soils being sands, and no quantitative measurement of SMC being provided, the results echo the results of this experiment, in that higher SMC required a greater heating time, but that the two textures reacted differently.

This area clearly needs more research and theoretical analysis, however, as noted in section 5.1 the open, batch, retort heating system is quite different to closed, continual-flow heat exchangers, so the results for such systems could be different again. This is therefore an issue where a watching brief is required and that may become clearer as the results from the concurrent experiments are collected. If further research is needed, then the methodology needs to be adapted so that an equal amount of water is added to each soil texture, so that the mass of the soils are the same, which will simplify thermodynamic comparisons. The standardisation of soil particle / aggregate size may also be required as this has been shown to have an impact on heating times in other ISTW experiments running concurrently. However, standardising particle / aggregates sizes for three such contrasting soil textures would be (1) difficult, and (2) possibly sufficiently artificial that the results may not be relevant to field conditions.

6.3. 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 soils in-situ. 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, e.g., 1.3-1.7 $g{\cdot}cm^3$ for sands and 1.1-1.6 $g{\cdot}cm^3$ 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 5).

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 (sand having no structure to start with) with the untreated control and lower SMC still retaining obvious structure while at the highest SMC structure was effectively destroyed.

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 as water is 1 $g\ cm^3$ and the soils ranged from 0.4 to 0.48 $g{\cdot}cm^3$

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 as there is no explanation for the result. Further, the crush weights do show a consistent trend for clay which is the more important measurement.

6.4. Crush weight

While the numerical differences in bulk density between soils and SMCs does not appear great, the differences in the crush weights is considered dramatic (Table 6). As hypothesized, sand does not form strong aggregates, and definitely not clods, so even at the highest SMC only 3.7 kg was required to crush the soil cylinder. At the other extreme clay required 1.3 tonnes to crush the soil cylinder for the highest SMC, clearly a very compact clod! Silt, though not forming as strong a cylinder as clay still required a very 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, will result in severe compaction / dense clods. While this is common knowledge among farmers who work such soils, i.e., it is not truly new information, it does however highlight the critical importance of taking a range of soil textures into account when designing ISTW machinery.

6.5. Final weights

The weight of the soil cylinders after drying are all below the 400 g starting weight (Table 7) which is to be expected as the soil drying cabinet is considered to more effective at drying soil than placing soil in a glasshouse, where humidity may have been higher, for example. In addition small amounts soil was inevitably lost during the heating, mixing, and compacting process, especially at higher SMC and particularly for clay and silt which stuck tenaciously to the treatment equipment. This is reflected in the decreasing weights for higher SMC. The final weight therefore provided a useful check that the soils were dry, especially the very compact silt and clay cylinders and that excessive amounts of soil were not lost during processing.

6.6. General discussion

It is considered the three hypothesis are well supported by these results. The different soil textures reacted differently to treatment in terms of heating times, bulk density and crush weight, especially at the higher SMC, i.e., the interaction of texture × SMC. The crush weight, being the key measurement of the experiment, unambiguously shows the potential for clay and silt soils to form dense clods from relatively moderate tillage at higher SMC, as would occur in some existing ISTW machines and were they followed by a compacting operation, e.g., a seed drill with press wheels, or the counter-flow hot air ISTW machine proposed in (Merfield, 2012b) that may require press wheels at the end of the treatment tunnels to provide an airtight seal.

The difficulty in handling silt and clay soils, due to their sticky nature, when close to field capacity is an issue that will need to be taken into consideration as part of ISTW machine design, as while it is considered less than ideal to till wet soils, in some situations working soils in marginal conditions is the reality in real-world farming. 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, the ability of ISTW systems to cope with such soil conditions may be of considerable importance.

Hypothesis 3 stated that increasing SMC will increase the time taken to heat the soils to the target temperature. Generally this was found to be correct, but there were clear variation among the different soil textures, plus the response to heating time among the different SMC was not proportional to the basic theoretical calculations of the energy required. It appears there is a greater level of complexity than simple thermodynamics indicate, for example, the effect of soil particle / aggregate size, how the textures interact with the steam, etc. This is considered to be a matter of direct importance to ISTW systems, and highlight the issue of continual monitoring of soil temperatures during treatment to provide a feedback / control system to ensure target temperatures are met, as discussed in (Merfield, 2012a, 2012b).

Anecdotal observations during the experiment highlighted the critical role of initial SMC on the amount of steam condensing in the soil samples. 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). Fortunately, this did not eventuate: the lower SMC soils all gained some moisture from the steam, as evidenced by things such as visual darkening of some soil aggregates and adhesion of some soil to the treatment basket, but without any obvious gross change in their SMC, e.g., becoming clearly wet. However, at the highest SMC, the additional water condensing from the steam took the SMC to field capacity, and with the sand, probably beyond field capacity as it appeared the extra water, heating and mixing induced liquefaction. However, it is possible that both high and low SMC soils absorbed similar amounts of liquid water from the steam, rather it was that the resultant effects were more obvious at the highest SMC as this took the soils past field capacity, a non-linearity in the physics of soil, which is visually obvious. These anecdotal observations need to be experimentally verified to determine how much water is absorbed by the three soil textures at a range of SMC. 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 avoided 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. Overall this issue may also require a watching brief.

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

It is noted that this experiment shows the combined effect of heating and tillage. It is not possible to determine how much, if any, effect heating the soil had in addition to the tillage / mixing, or the reverse, heating without tillage / mixing. 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, in that they are easily compacted into dense clods which have significant negative effects on plant growth. 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.

7. Conclusions

This experiment has clearly shown that heating, tilling, and compressing silt and clay soils, especially at higher SMCs results in the formation of dense, very strong clods / compaction, which are widely known, both from research and practical farmer experience, to cause a significant, if not very significant impediment to crop growth. Sand soils do not react in this way and their structure is effectively unaltered by such treatment. It is therefore not possible to assume that ISTW treatments that work on sandy soils will perform satisfactory on wet silt and clay soils. Therefore if ISTW systems are to be practical on a wide range of soil types, the issue of compaction of silt and clay soils needs to be taken into account.

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