Intrarow Soil Thermal Weeding Supplemental Report: An Analysis of the Potential for Ex-field Heat Treatment

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2. Introduction

Following the publication of "Expanding the potential of intrarow soil thermal weeding" (Merfield, 2013), additional analysis has been undertaken of the potential for 'ex-field' intrarow soil thermal weeding (ISTW) as an alternative to the 'in-field' soil heating covered in the report. This analysis has found ex-field ISTW to have a number of benefits, but also issues, that need clarifying.

This report gives a brief explanation and analysis of the ex-field ISTW approach, with the recommendation that research into its feasibility should be conducted in parallel with in-field ISTW research.

3. In-situ, vs. ex-situ vs. ex-field

In Merfield (2013) the potential for both in-situ and ex-situ soil treatment for ISTW was analysed. In-situ treatment means that the intrarow soil is treated by mobile machinery in the field without removing it from the bulk soil, i.e., treated soil remains both in place within the soil and also within the field. Ex-situ soil heating means that soil is removed from the bulk soil / field surface for treatment, but that it was still processed on mobile machinery within the field, in real time, and then replaced back into the bulk soil. In comparison to both in- and ex-situ treatment, ex-field ISTW treatment, involves physically collecting and removing soil from the field and then treating it in a separate location and time, i.e., 'outside' the field. To distinguish these two approaches the in-situ and ex-situ systems discussed in Merfield (2013) are called 'in-field' systems and this system is called 'ex-field'.

The ex-field approach has been previously suggested in various permutations, by Paul Mesman in 2007 (then of Canesis Network Ltd) and in 2013 by Ian Domigan (Lincoln University), but had been previously ruled out as less favourable than in-field treatment, primarily due to the logistical complexity of dealing with the large amounts of soil involved. However, the findings of Merfield (2013) highlighted a number of challenges with in-field treatment, particularly for hot air heat-recycling systems, which mean that the advantages of ex-field systems may outweigh the disadvantages, and therefore that a deeper analysis of ex-field systems is required.

4. Ex-field ISTW practicalities

Ex-field ISTW is based on removing soil from a field, weeks to months ahead of the planting date, progressively treating the soil 'outside' the field, e.g. on the headland, farmyard, etc., then storing it until required, before placing it back into the field as intrarows, potentially in a single pass operation combined with drilling, to placement a few hours, to days to possibly months prior to planting.

4.1. Soil volumes and weights

The key problem with ex-field ISTW is the volume / weight of soil involved. For example, a 1.8 m bed system with four rows per bed and a 5×5 cm intrarow requires, at a **theoretical minimum**, 56 m^3 / 89 tonnes of soil per hectare (at 1.6 tonnes·m^3 bulk soil density) and for a 7×7 cm intrarow, 109 m^3 / 174 tonnes. While these are considerable amounts of soil to move while keeping to a bed or controlled traffic system (which would be essential to manage compaction), they are considered to be within practical limits, e.g. 89 tonnes is equivalent to top-end yield from a crop of potatoes, and 56 m^3 (5×5 cm intrarow, as above) is slightly less than the volume of a standard 40' shipping container (intermodal container) at 68 m^3 (this is not to say that shipping containers would be of use, it is just to give an intuitive description of the volumes involved).

To manage these amounts of soil while minimising compaction, a 'headland' system would most likely be required, where the in-field machinery only carries small amounts of soil, e.g. one or two field-lengths, which is then transferred to a headland based bulk carrier (e.g. tractor trailers). This would apply to both soil removal and replacement.

4.2. Removing soil

For ex-field ISTW the soil for treatment does not have to be removed from the intrarow: any soil from the plough layer / A horizon would be suitable. This should simplify soil removal considerably, for example a few centimetres of the top of the soil could be 'planned off' with an 'earth-scraper' type machine, e.g. based on the design of shallow, bed width harvesters such as onion lifters. These are able to deal with a wide range of soil textures, moistures, residues and to some extent stones. The soil surface also tends to be the driest, which also has a range of benefits.

In addition, soil would not have to be removed from every bed, but, say, every five to ten beds, depending on factors such the evenness of the field and, if there will be subsequent tillage etc. The soil does not even have to come from the same field where it would be used, which would allow even greater flexibility, though there will be limits due to the cost of moving large amounts of soil over significant distances, concerns about mixing different soils, or mining fields with 'good' soil to create intrarows in fields with 'poor' soil.

Further advantages are: that the soil can be removed well in advance of when it is needed allowing plenty of time for treatment. Removal can also be timed to fit in with other farm operations, e.g., quiet times. Soil removal could also be times for when it is in the optimum treatment condition, i.e., dry, and therefore at its lowest weight and when its handling characteristics are most manageable.

4.3. Pre-treatment

One of the key problems of in-situ and especially ex-situ, in-field ISTW is the 'soil handling problem' (Merfield, 2013), where the very different physical characteristics of sand, silt and clay soils, which, in turn, can be radically modified by soil moisture, plus the complexities introduced by aggregation, the presence of plant residues and stones and the small volumes of soil involved, makes soil handling very challenging. These are all considered to far more manageable with the systems described above as these are already in existence, in various forms, e.g. bed harvesters, so adapting these for soil collection is considered straightforward 'farm-engineering'.

Once the soil has been collected, the use of a pre-treatment system that optimises the soil for the heat-treatment system could have many benefits. The key factors involved are:

- Soil moisture content (SMC) needs to be sufficiently reduced to make handling easy, e.g. below the adhesion threshold and plastic state;
- Reducing moisture will also address the evaporative cooling effect of water with hot air heating;
- Aggregate size can be optimised for soil handling, heat transfer and soil structure (i.e., not made too small so structure is lost);
- Plant residues, stones and other adventitious material can be removed simplifying handling and treatment equipment.

Once soil is in the holding containers (e.g. farm trailers) SMC can be reduced without difficulty by 'pumping' ambient air through the soil when atmospheric temperature and relative humidity (RH) are suitable, as is done for cooling and/or drying a wide range of horticultural produce, e.g. apples and onions. The soil could also potentially be pre-heated (warmed) by such an approach (e.g. through only pumping air on warm / hot days), although with a heat recycling system the benefit of this are considered to be small.

Once the soil is sufficiently dry for easy handling, aggregates, stones and plant residues can all be managed using rotary screen separators, and crushing mechanisms, which are both simple and well established technologies (see Merfield (2013) for examples).

The pre-treatment process can thus optimise soil for heat treatment, using simple, well proven, reliable technologies, which should considerably simplify the heating process as problematic soil characteristics have been considerably reduced. In addition, it will also facilitate handling of the soil for replacement into the intrarow - which was considered a significant problem for in-field, ex-situ ISTW approaches.

4.4. Heat treatment

As both, the need for very rapid soil heating and cooling / heat recovery, and the need for heating machinery to fit within the constraints of in-field agricultural equipment, do not apply to ex-field ISTW, the treatment process can solely be optimised for:

- Minimum energy use;
- Maximum seed mortality;
- Mechanical simplicity.

The basic concept is based around holding the soil in purpose designed mobile storage containers, i.e., trailers that can be towed by tractors. Soil would be initially dried in the containers by pumping ambient air through them. The soil would then be screened and crushed, by removing it from one trailer, processing it, and transferring to a second trailer. The pre-treated soil would then be heat treated, again via a transfer between trailers. Treated soil would then be stored in the trailers until required.

4.4.1. Initial design concepts

- Soil should be easy to move with well established engineering / technologies, e.g. augers and conveyor belts, between storage trailers, pre-treatment and the heat treatment systems.
- The heat treatment system is based on the two, in-series counterflow heat exchangers, one to heat and the second to cool soil and reclaim the heat (as described in Merfield (2013)).
- However, as fluidised beds have been ruled out (Merfield, 2013) alternative means of mixing soil and air will be required. It is considered that the heating / cooling air can be 'pumped' through the soil as it moves downwards under gravity in a tower (possibly with mechanical assistance / agitation). Soil would be moved in and out of the tower with augers or similar technology.
- The air pressure × volume × temperature parameters can be optimized for maximum weed kill and thermal efficiency:
  - The pressure of the air is determined by the force required to 'push' the air evenly through the soil being treated;
  - The temperature of the air need only be at the target treatment temperature, due to the thermodynamics of counterflow heat exchangers) which will allow for maximum efficiency and simplify the engineering (e.g., no requirement for high temperature tolerant steelwork);
  - The volume of air is then determined by the treatment temperature and air's specific heat.
- The treatment vessels will need to be highly insulated, even to the point of using vacuum containers, to ensure minimum heat loss, because the machines will be running for long periods, so even small heat losses can add up to a large total heat loss over the time needed to treat large volumes of soil.
- After heat treatment, the soil is stored until required. As it is in a dry state there should be minimal further effects on soil properties even after extended storage as long as it is kept dry.

4.4.2. General considerations of ex-field heating

The soil in storage, both before and after treatment, acts as a 'time' and 'location' buffer allowing machinery design considerations to solely focus on optimising the treatment process, rather than trying to fit treatment into the constraints of an in-field system. Soil storage, both untreated and treated, allows ex-field ISTW work to fit into farm management timelines, rather than farm management having to fit around in-field ISTW treatment.

In terms of seed mortality the research in Merfield (2013) indicated that the rapid heating and cooling required for, and associated with, in-situ ISTW resulted in significantly increased weed seed survival. Ex-field treatment times can be far slower, by several orders of magnitude, than in-field treatment, so that extended heating times can be used to ensure complete seed death.

In addition, if the hypothesis in Merfield (2013) about thermal-time being the key determinant of seed mortality, extended heating times should mean that lower treatment temperatures, e.g. 70°C, could be used, which could have a number of advantages, e.g. simplifying engineering, reducing heat loss, reducing other negative effects on other aspects of soil biology, etc.

The combined benefits of reduced treatment temperature, simplified soil handling, and no need for very rapid heating and cooling, mean that the heat exchangers can be optimised for heat recovery, i.e., close to maximum theoretical thermal efficiency can be achieved. This means that potentially very small amounts of energy / fuel are required, e.g. 20 L diesel·ha^{-1}, as the primary energy requirements are for initially heating up the equipment and the first 'fill' of soil and to compensate for energy losses due to imperfect insulation and less than 100% efficient heat exchange between soil and air.

4.5. Soil replacement

When the treated soil is required for use, it can be placed into the intrarow by reversing the removal process. Soil is taken to the field's headland in the trailers. These unload small volumes of soil (one or a few field runs) into a tractor mounted applicator, which consists of a hopper, from where soil is metered to the intrarow placement units, which open / cut a slot in the bulk soil of the required dimensions which is then filled with the treated soil and firmed. This operation should be much faster than in-situ ISTW treatment, and would be less influenced by soil conditions. Forward speeds of 4 kph seem reasonable, and multi bed systems are also a possibility.

As the treated soil will be dry, it will need to be moistened before it can be used for planting. If the bulk soil is wet, it would be expected that capillary action and other soil moisture transfer mechanisms would wet the soil to equilibrium with the bulk soil in a few hours to days. Alternatively, if the bulk soil is too dry, irrigation can be used, though soil splash of weed seeds from the bulk soil into the intrarow may be an issue. It may be possible to drill seeds directly into the treated soil, e.g. as one field operation, and then wet the soil afterwards. Seeds could also be drilled into soil that has moistened up.

5. Pros and cons

5.1. Thermodynamic, engineering and biological

5.1.1. Pros

- As there is no requirement for rapid heating, the heating air only needs to be at the target soil temperature, as this will give the maximum efficiency in the counterflow heat exchangers. This also means that the air coming from the heat recovery exchanger will effectively be at the same temperature as the primary heating air, so non of the issues of mismatched air pressure × volume × temperature parameters that potentially exist with in-field ISTW apply, which addresses one of the biggest problem for heat recovery with in-field ISTW systems.
- Slow treatment rates should ensure maximum seed death - plus treated soil can be tested before use, or as part of a continual monitoring system.
- The issue of aggregates heating more slowly and therefore providing seed refugia is avoided as the heating process can be slowed below the rate of heat conduction within aggregates, so even the centers of aggregates are heated for the required temperature × duration, thus ensuring complete seed death.
- There is considerable potential to match the heat treatment system power requirement to readily available slow-response, constant heat output systems, e.g. renewable systems such as wood chip, straw and other biomass burners.

5.1.2. Cons

- As soil and therefore seeds will be dry, this may require a longer heating duration and/or higher temperatures compared with wet heat such as steam or wet soil. Research into the effects of moisture × heat × duration are therefore considered even more critical for ex-field compared with in-field ISTW.

5.2. Practical (farm management) and agronomic pros and cons

5.2.1. Pros

- Much lower energy use due to optimisation of heat recovery, which means lower fuel costs, though the total costs (e.g. cost of lots of trailers vs. one in-situ machine) are currently uncalculated.
- The total amount of power (watts) required could be very small, e.g. a few kilowatts, compared with in-field (real-time) heating potentially requiring megawatts. The power requirements may be within reach of standard amperage electricity supplies or at least within the capabilities of on-farm three-phase power supplies, making for very simple heater engineering, i.e., electrically heated air.
- If treatment is to occur away from mains electricity, simple fuel burners, e.g. naturally aspirated gas fuel burners could be used. Solar thermal and/or solar voltaic power sources are also possibilities, along with other renewables, e.g. wood chip power systems.
- If biomass fuels (straw, wood, etc.,) can be used, these may be 'waste' farm products and therefore carry a very low actual and/or economic opportunity cost which could further reduce / internalise running costs.
- Soil can be placed in the intrarow weeks even month ahead of use, as no weeds will grow in the treated soil in the interim, although the untreated soil bulk will produce weeds that may require management.
- High field work rates for replacing soil could be a significant advantage during the high work-load periods, e.g. spring.

5.2.2. Cons

- Removing, storing and replacing large volumes of soil is a considerable logistical exercise and will require good planning to ensure treatment is complete in advance of the soil being needed.
- While the cost and complexity of the heating system itself is likely to be much lower than in-field ISTW machinery, there is potentially considerable cost and complexity in terms of the soil removal, treatment, replacement machinery and particularly multiple trailer storage units, which could be equal to, or even greater than in-field ISTW machinery.

6. Conclusions

On the basis that in-field ISTW systems can be made to work, the relative benefits from a farmer's and grower's perspective is considered to be primarily the overall cost and practicality of the two systems.

In-field ISTW systems are 'just like' other field operations, i.e., a tractor drives up and down the field so it is easy for farmers and growers to comprehend and implement the idea. Ex-field systems are unlike any other field operation so a change in mindset is probably required.

Ex-field systems have a considerable 'management buffer' in that operations can be timed to fit in with slack periods in farm work and when field conditions are optimal (i.e., dry) but require more planning. In-field systems have to be used when crop-programming requires the fields to be ready, which are likely to have a much narrower window of opportunity, which is a particular risk with the likely slow operating speeds of in-field equipment and the need to have soil in the right condition / tilth prior to treatment at times of year when the weather is often not in favour of field operations.

Finally what suits one producer may not suit another and therefore both systems could be required.

It is therefore considered that research into in-field and ex-field ISTW systems should be conducted in parallel, so they can be compared and contrasted, especially the economics, practicalities and energy consumption.

7. References

Merfield, C. N. (2013). *Expanding the potential of intrarow soil thermal weeding*. Lincoln: The BHU Future Farming Centre http://www.bhu.org.nz/future-farming-centre/information/weed-management/istw