# Thermal Band Heating for Intra-Row Weed Control

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**Abstract**
For many years, disinfection of the soil by means of steaming has been a common method for eliminating weeds and fungal diseases. However, surface steaming of soil is a very energy-intensive process, and consequently, efforts have been made to develop a machine for narrow-band steaming of the soil under and around rows of cultivated plants prior to seeding. The use of this machine may achieve up to 90% energy savings, and will also reduce the amount of damage to the flora and fauna. A special test rig has been developed with the objective of obtaining new information about narrow-band soil steaming. The test rig consists of a revolving ditch, in which the soil can be heated by means of submerged steam jets. The rig is equipped with thermosensors for measuring temperatures in the steamed band during the process. For a more detailed analysis of the temperature profile in a cross-section of the processed band, an apparatus has been developed especially to record the temperatures obtained at 63 locations and at seven levels across the ditch. On the basis of the results from the test rig, a prototype band-steamer for field use has been developed. Tests have shown that soil temperatures exceeding 70°C will be needed to protect against germination of weed seeds. For band heating such a treatment in 50 cm rows requires about 5.8 GJ/ha.

## 1. Introduction

For many years, thermal soil treatment has been a well-known and frequently used method for eliminating weed seeds and fungal spores. The method has commonly been used for the disinfection of soil in greenhouses. Heating may be done either by pointing a gas flame towards a revolving drum filled with accumulated soil (Shaw & Mitchell, 1977) or by injecting steam directly into the plant beds (Pizano, 2001). The steam is usually produced in an oil-burning steam boiler. Heating by means of steam is also used in outdoor plant beds, where the steam is injected into the soil from a closed chamber of the same width as the plant beds (White et al., 1999). This is an effective soil disinfection method, destroying fungal spores and weed seeds. However, since all the soil in the beds is heated to a depth of 10–20 cm, the method is very energy-intensive, and requires the consumption of 3000–5000 l of oil per hectare (White et al., 1999).

In an attempt to reduce the direct energy consumption involved in surface steaming, KOH or CaO have sometimes been added to the soil during the steaming process, as these substances are capable of absorbing water by an exothermic reaction (Peruzzi et al., 2002). However, in general, no energy savings seem to have been obtained by using this method, due to the high energy costs of producing the KOH and CaO. Furthermore, the large quantities of calcium or potassium added to the soil may be difficult to accommodate in a fertilisation schedule.

Most vegetables are grown in rows, and automatic vision-controlled equipment for the elimination of weeds between rows is currently available commercially (Tillett et al., 2002), although automatic, “non-chemical” systems for the effective elimination of weeds in the intra-row area are not available. One way to eliminate intra-row weeds without the use of chemical agents could be to destroy the germination capacity of the weed seeds under the rows by heating a narrow band of soil around the rows to about 70–90°C before seeding. As only a very few weed species will germinate from deep soil layers (White et al., 1999), only the topmost 5 cm of the soil will need to be heated. By heating only a narrow band of 6–8 cm around the rows to a depth of 5 cm, energy savings of more than 90% can be anticipated, compared with a full steaming of the entire soil surface. In practice, the system may be combined with a computer-controlled sowing machine for the subsequent sowing of plants in the centre of the treated bands. The system will result in the crop growing in rows free of plant competition. This also provides favourable conditions for the functional capacity of a subsequent operation involving vision-based row guidance.

## 2. Materials and methods

When steam is used for soil heating, its ability to transfer energy to the soil, e.g. during combustion of oil, can be exploited, as the evaporation energy of the water will be released when the steam condenses into the soil. In order to limit heat loss to the air, it is essential that the soil surface is only heated enough to destroy the germination capacity of the weed seeds. In this project, the steam will therefore be released at some distance below the soil surface by means of purpose-built steam jets. The design and control of the jets allows the process to be reliably controlled so that the temperature remains stable relative to the required value and the temperature profile is uniform throughout the soil band. The purpose of the work described here was to set up the design conditions for the process unit.

### *2.1. Experimental test rig*

To enable the dimensioning and designing of the steam jets, as well as testing the heat treatment of soil samples under controlled conditions, a laboratory rig with a soil capacity of 33 l was constructed. The test rig consists of a 105-mm-thick, 1220-mm-diameter horizontal revolving disc with a variable rotation speed (rpm). The upper part of the disc consists of several loose rings of different diameters. In order to create a ditch 85 mm deep and 50–170 mm wide, the rings may be added or removed as necessary (see Fig. 1). The ditch can be filled with soil, which can be heated by means of steam. The steam is sprayed out from four jets that are lowered into the soil during the operation. The test rig is used for two sets of experiments; one to determine the process temperature needed to destroy the germination ability of the weed seeds and the other to address the design challenge of obtaining a uniform temperature in the processed soil profile. For the first analysis, the ditch is made narrow around the jets and the chamber is isolated. For the analysis of the temperature profile, the ditch is made broader to involve the heat transfer to the surroundings.

#### *2.1.1. Steam generators*

Each steam jet is supplied with steam from an electrically heated steam generator designed for cleaning purposes. The steam generators can be controlled by a pressure switch, which will interrupt the heater at a pressure of 4 bar. The steam can be turned on/off by means of four magnet valves placed in the generators; all four magnet valves may be turned on at the same time. The steam generators each have a nominal effect of 2.2 kW, and the maximum output from all four generators will be 8.2 kW.

#### *2.1.2. Injection tines*

A steam jet consists of a flattened pipe that can penetrate the soil to a depth of 4–5 cm. The lower end of the pipe is closed, and the upper end is connected to the steam generator by a rubber hose.

Steam is ejected through two 1.5-mm-diameter holes placed at the side of the jet, 10 and 30 mm from the tip. The four steam jets are mounted on a cross-shaped frame over the revolving ditch. Two jets are placed on either side of the treated soil band with the jet openings pointing toward the soil band. On either side, the jets operate at depths of 4 and 5 cm, respectively, under the soil surface to ensure a four-level injection of the steam at either side of the soil band, i.e. 1, 2, 3 and 4 cm under the soil surface.

*2.1.3. Thermosensors in the heated band*

During steaming and cooling of the soil, the temperature of the heated soil band is measured continuously by means of 12 thermosensors connected to a datalogger. The thermosensors, which consist of thin soldered-type K thermocouples, are mounted on four vertical tubes at three levels. Two of the sensor tubes are placed in positions where they will be able to measure the soil temperatures about 10 mm from either side, while the other two tubes will measure the temperatures at the centre of the soil band. The individual thermosensors are cleaned of soil every time a new soil band is exposed to steaming.

*2.1.4. Thermosensors in the cross-section*

In order to obtain more accurate results from the temperature measurements of the treated soil band and the surrounding soil, a special temperature-monitoring apparatus has been developed (see Fig. 2). The apparatus consists of 63 vertical thermosensors placed in a 120 × 160 mm grid at intervals of 20 mm. Designed for manual compression into the soil, the apparatus will measure the temperatures at seven different soil depths from 0 to 6 cm from the soil surface for every 20 mm across the treated soil band. For technical reasons, the seven measurements will not be made at exactly the same locations, but at seven different locations at intervals of 20 mm along the soil band. The distribution of the seven longitudinal levels will be chosen at random.

The sensors consist of soldered-type T thermocomponent conductors that are wedged on to the tip of a 4 mm stainless steel tube. At the touch of a single key, all 63 temperatures are recorded and memorised by a datalogger within about 2 s.

*2.2. Measurement procedure*

The test rig was primarily used for steam heating of different soil samples with a known content of weed seeds at temperatures of 60, 70, 80 and 90°C. During the steaming, measurements from 12 fixed thermo sensors are averaged as measure of the mean temperature of the soil sample. Readings of the calculated mean temperature are made continuously, and when the desired temperature is reached, the steaming is interrupted. The soil sample is left untouched for 10 min in the ditch before being prepared for the subsequent germination analysis, which takes place in a greenhouse under controlled conditions. The number of plants that germinated was counted every week over a period of 3 months.

The test rig was also used for an estimation of the efficiency of energy transfers from steam to soil and of the heat-energy distribution between the heated band and the surrounding soil. For these measurements, a ditch width of 170 mm was used, although the width of the steamed soil band at the centre of the ditch was only about 6 cm. In order to reduce the heat loss to the air, the soil was covered by a rubber lining during the steaming period (150 s). Immediately after steaming, the rubber lining was removed, and the soil temperatures were measured at 63 different points by means of the instrument described above. After that, the temperature distribution was again measured three times at random points within the soil band at intervals of 2 min in order to observe the heat distribution in the soil during the cooling period.

## 3. Results and discussion

### *3.1. Treatment of soil samples containing weed seeds*

The purpose of the soil sample steaming was to study the effect on the weed seeds when different soil types with varying water contents were exposed to steaming. Figure 4 shows the temperature increases for the soil samples during the steaming period. Each curve represents the average of four measuring points, at the bottom, at the centre and at the top, across the 5-cm-deep soil band.

The soil band was first heated at the centre, and the heat then gradually spread to the top and the bottom of the band. The reason for the steam being injected into the central part of the soil band was in order to reduce the heat loss to the surroundings during the steaming period.

Figure 5 shows the results of the germination tests, with the number of surviving weed plants in relation to the treatment temperature. The results show that at a temperature of about 65–70°C the weed seeds generally lose their ability to germinate. From a technical point of view, this means that the control system for field application has to ensure that the temperature in the processed soil band uniformly reaches at least 70°C. However, higher temperatures mean a loss of energy, especially if they rise to 90°C, when evaporation of soil water starts to take place. The challenge is to design the field application system such that the required conditions are met.

### *3.2. Measurement of efficiency in heat transfer from steam to soil*

The purpose of the measurements described below was to carry out energy flow studies during soil steaming. The treated soil was therefore not exposed to germination testing. The soil types used for the measurements were sandy soil or clay soil. Both soil types were examined at two different moisture contents. The main issue under investigation was the efficiency obtained during the transfer of steam energy to soil, in order to determine how much energy would be transferred to the air during steaming. Therefore, all the soil in the test rig ditch was used for calculation of the total energy absorption.

Prior to the energy measurements, the specific heat rate for the dry matter contained in the two soil types was determined calorimetrically at 0.858 kJ/kg*K for the sandy soil and 0.896 kJ/kg*K for the clay soil. Afterwards, the specific heat rate for the applied soil portions was estimated on the basis of a given soil moisture content.

To measure the maximum steam production of the steam generators, the steam jets were immersed in a basin filled with cold water, after which the total increase in the basin mass in relation to the elapsed time was measured. By multiplying the steam production by the heat of vaporization of water, an output of 8.2 kW was calculated.

The primary results from the energy measurements for the total soil mass are shown in Table 1. Each value represents the average of three individual measurements for the same soil type.

An efficiency of 91–100% was obtained by transferring steam energy to the soil. The loss of efficiency (0–9%) was due to the loss of steam to the air. The lowest losses were observed on dry soils. This is probably due to the fact that dry soil exposed to steaming will absorb the steam more easily than the moist soil will.

### *3.3. Heat diffusion from the steamed band into the surrounding soil*

From Table 1 it can be seen that the energy loss to the air was insignificant during the heating period. However, a considerable amount of energy was transferred to the surrounding soil, as indicated in Figure 3. In a sectional view of the ditch, Figure 3 shows the 63 recorded temperatures 40 s after the steaming ended. For clarity, different colours have been used to indicate the temperature ranges according to the scale shown at the left-hand side of the Figure.

The 6 × 5 cm steamed band in the middle of the ditch is clearly indicated, but it is also obvious that the soil on both sides of and beneath the steamed band has also been heated to some degree. The thermosensors must be kept in the soil for about 30 s before the reading can be considered reliable. The soil temperatures could therefore not be recorded immediately after the steaming, but only about 40 s later. This may explain why the temperatures at the surface were noticeably lower than those measured 1 cm below the surface (the same difference was not seen from the supplementary soil temperature measurements immediately underneath the rubber lining until it had been removed).

In order to determine the temperatures in the steamed band immediately after the end of the steaming, the diagram in Fig. 6 shows the soil temperature values measured in the steamed band during the first 400 s after the steaming had finished. By extending the curves obtained towards the *y* axis, it should be possible to estimate the temperatures at the end of the steaming. The same method was used to determine the mean temperature increase, as shown in Table 1.

Figure 5 shows that for all soil types the final estimated temperature exceeded 70°C. Affiliated research by Melander et. Al. (????) shows that such high temperatures are necessary in order to destroy the germination capacity of the weed seeds. However, after steaming the temperature will decrease rapidly to less than 70°C. As the soil surface temperature will decrease faster than the mean temperature, the entire soil band will have to be heated to a somewhat higher temperature in order to ensure that the temperature of the weed seeds at the soil surface exceeds 70°C for a long enough period before the soil cools down again.

In subsequent field trials investigating the steaming of narrow soil bands, increased effects on weed germination were observed at increasing treatment temperatures up to about 90°C.

### *3.4. Energy efficiency in the steamed band*

As shown in Figure 3, some of the energy is transferred to the surrounding soil, where it will be of no use, because the temperatures obtained will be below 70°C. However, it should be mentioned that the relatively low steam-generator output used here required a steaming duration of 150 s, which was sufficient for the heat to be transmitted widely to the surrounding soil. Under practical field conditions, the capacities of the steam generators will be much higher, and thus the steaming will need to last only a few seconds.

By comparing the volume of the soil in the steamed band with that of the soil in the entire ditch, the soil mass in the band can be estimated quite precisely, and by comparing the soil mass with the achieved temperatures, as shown in Fig. 6, the energy absorption in the soil band can be estimated. By relating the energy utilisation to the energy liberated from each soil type, it will be seen that the efficiency is reduced to 50–60%. Under practical field conditions, the heat loss will be smaller, while the efficiency of an oil-fired steam generator will be lower than that for small, electrically heated steam generators. Therefore, total efficiencies higher than 55% will not be feasible under practical field conditions.

For the steaming of 6-cm-wide and 5-cm-deep soil bands with a row interval of 50 cm, 60 $m^3$ of soil should be heated per hectare. For soil with the same density and the same water content as “normal clay”, about 5.8 GJ/ha should be used in order to obtain a net temperature increase from 10 to 80°C. For an efficiency of 55%, this will correspond to a consumption of about 300 l of diesel oil per hectare.

## 4. Conclusions

An experimental test rig, used for steaming soil samples mixed with weed seeds and for examining the thermal efficiency involved in soil steaming, has been developed. From steaming soil samples containing weed seeds in an isolated ditch in the test rig, it was seen that soil temperatures exceeding 70°C will be needed in order to destroy the germination capacity of the weed seeds. In connection with the transfer of steam energy to the soil, efficiencies of 91–100% were found for soil temperature measurements at 63 points and at seven levels across a 170-mm-wide ditch. Part of the energy will, however, be transferred to the soil surrounding the steamed band, and therefore, in the case where a 6 × 5 cm soil band is exposed to steaming, the efficiency will only be 50–60%. For an efficiency of 55% and a row interval of 50 cm, about 300 l/ha of oil will be needed to heat a 6 × 5 cm soil band to a temperature of 80°C.

On the basis of the experiments in the test rig, a prototype one-row band steamer has been developed for field purposes. Good results have been achieved from the preliminary tests. However, further development efforts are needed before the machine will be ready for production.

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**Fig. 1.** Experimental test rig for soil heating by injection of steam

**Fig. 2.** Instrument for measurement of soil temperatures across the heated band

**Fig. 3**. 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.

**Fig. 4.** Soil temperatures measured at three levels in the soil during the steaming process

**Fig. 5.** Number of surviving weed plants in relation to the treatment temperature

**Fig. 6.** Temperatures in the steamed band from 40 to 400 s after the end of the steaming in four different soil types

**Table 1.** Transmission of steam energy to soil

| Soil type | Moisture, % DB | Specific heat, KJ/kg*K | Soil mass, kg | ΔT in soil, °C | Energy received, MJ | Energy delivered, MJ | Efficiency, % |
|---|---|---|---|---|---|---|---|
| Normal sand | 8.7 | 1.124 | 36.51 | 27.6 | 1.133 | 1.230 | 92 |
| Dry sand | 5.6 | 1.035 | 40.00 | 28.1 | 1.163 | 1.230 | 95 |
| Normal clay | 10.0 | 1.195 | 37.82 | 24.8 | 1.121 | 1.230 | 91 |
| Dry clay | 8.8 | 1.162 | 38.92 | 27.2 | 1.230 | 1.230 | 100 |

**Figure 1.** Experimental test rig for soil heating by injection of steam

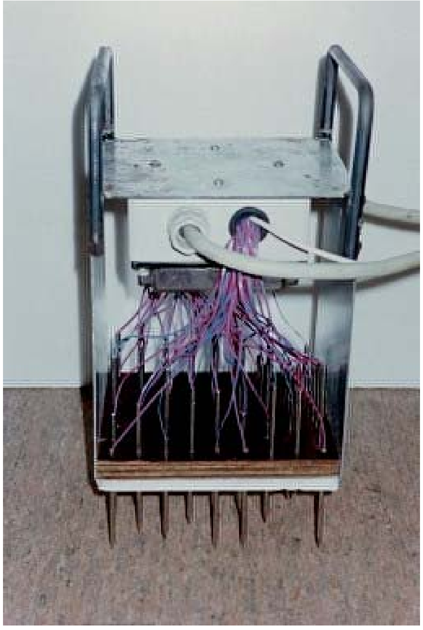

**Figure 2.** Instrument for measurement of soil temperatures across the heated band

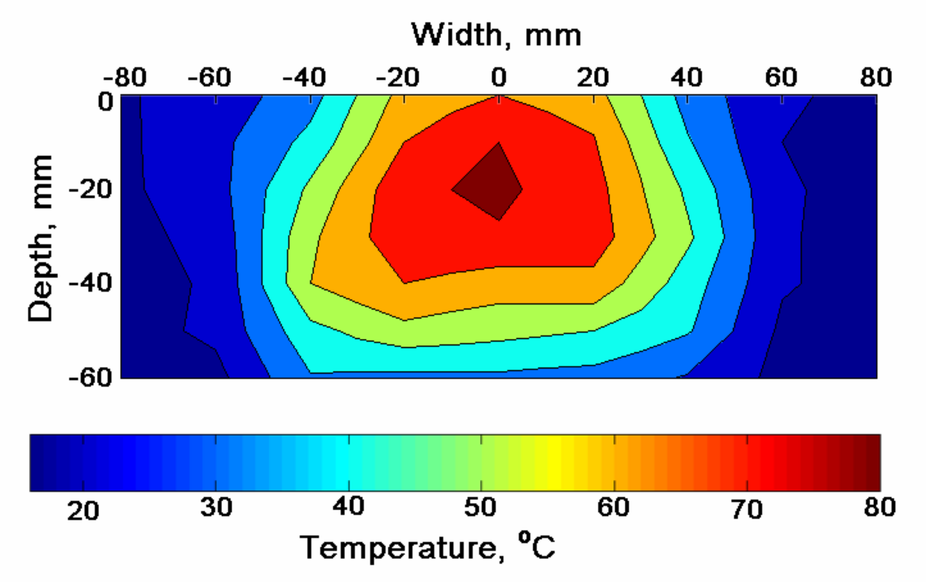


**Figure 3** Soil temperatures from a cross-section across the groove, measured 40 sec. after treatment. The width is measured from centre of the treated band. Treated area: With –30 - +30, depth 0 - 50 mm.

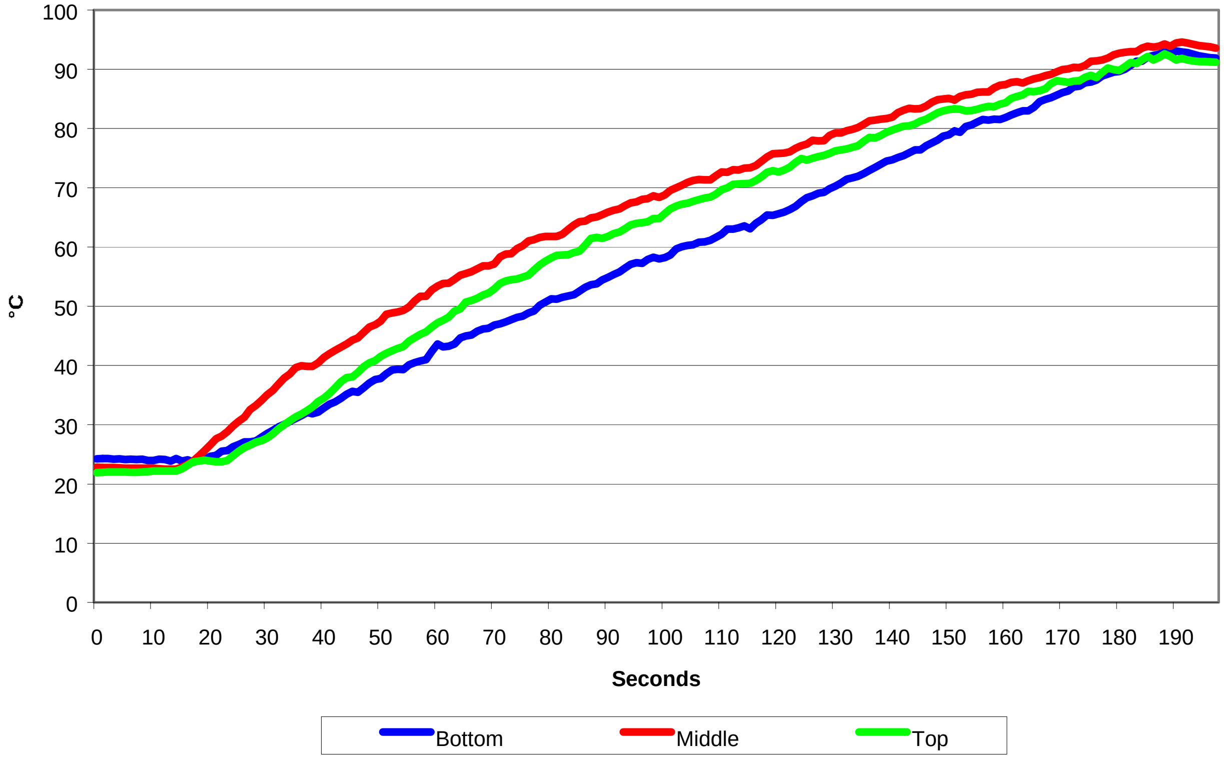


**Figure 4.** Soil temperatures measured at three levels in the soil during the steaming process

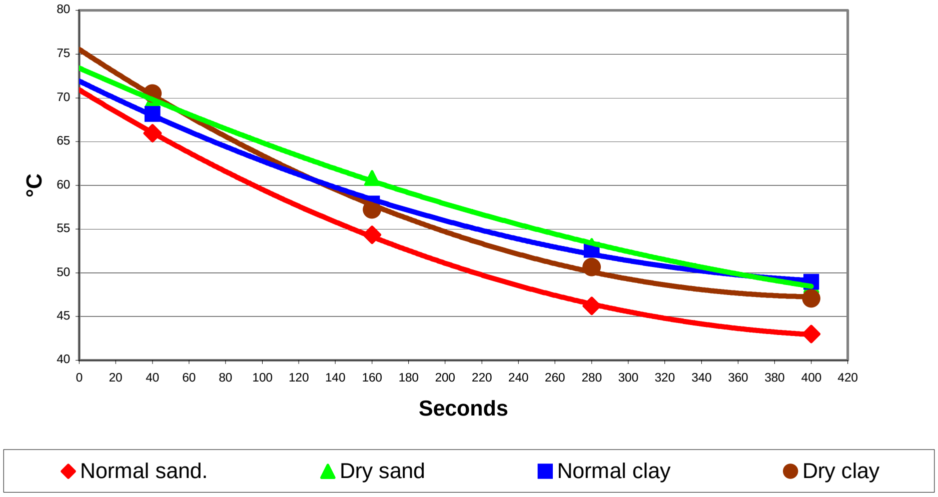


**Figure 5.** Temperatures in the steamed band from 40 to 400 s after the end of the steaming in four different soil types