Assessment of the potential for mobile soil steaming machinery to control diseases, weeds and mites of field salad and related crops.

Conducted on behalf of
Horticulture Research International

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PRACTICAL SECTION FOR GROWERS

The basis of this project was to test the effectiveness of mobile soil steaming machinery on a range of soil types around the country in order to quantify its effectiveness against common soil borne pathogens, weeds and *Tyrophagous* mites.

Growers of short term field salad crops and those in a number of other sectors will lose the present benefits from the use of methyl bromide when legislation restricts its use early in the next Millennium. A suitable alternative needs to be found to ensure that growers have access to technology, which will enable them to continue production to the specifications of their customers. Growers must rapidly find alternative sterilant, or disinfectant, treatments. Put in the most direct terms, that objective could be met by a chemical treatment of 1,3-dichloropropene applied with chloropicrin under polythene sheeting. This treatment has been shown over and over to be close to the methyl bromide standard. However, it requires contractors for application, time for the chemicals to disperse, and the very nature of those chemicals means that the general public would not sympathetically receive them. A non-chemical alternative, which could be used for the foreseeable future, has considerable attractions. Growers have chosen to investigate soil steaming as that potential alternative.

One of the potential sources of steam treatment machinery is the mobile steaming equipment available in France and widely used by small-scale growers. The concern of the Speciality Produce Growers' Association was that this machinery may not be efficacious, or operate at coverage which could be of true benefit to large-scale producers in the UK. As a result a Regero self-propelled soil steamer was imported from Nantes and tested with three growers widely separated in the South of England.

This study shows that all pathogens tested including *Pythium* were killed within the first 5 cm layer of any soil type except heavy aggregate clay. The majority of pathogens were killed, and all reduced in number, down to 10 cm. Below these depths soil type, soil consistency and moisture content played an increasing role in the effectiveness of the treatment. Native *Pythium* populations did not recover during the three month period of trialling suggesting that re-colonisation may not affect growing crops for some time. Within the zone of treatment, field steaming was very effective in controlling the majority of weeds. However bed edges and wheelings did pose a problem and may require adaptation of the existing machinery or the inclusion of additional control measures.

Well rotovated light sandy soils, seen at Grower 3, allowed much deeper steam penetration and therefore greater control. Heavy clay soils containing large aggregated clods, seen at Grower 1, did not allow steam to penetrate and therefore provided a refuge for pathogens or weed seeds nearer the surface; these clods with surviving pathogens may act as foci of infection within a crop. Penetration of steam is at an optimum when soil is tilled and just wet enough to be squeezed in the hand without loss of water. The basic requirements for field preparation pre-steaming are therefore the same as for methyl bromide. Sufficient water must be available for pathogens and seeds to be hydrated but not so much that it prevents the progress of steam through the soil. The steaming process increased the percentage soil moisture by about two percent.

Post steaming problems could be caused by seed shedding by any surviving weeds or by crops grown for their seed. Post steaming soil cultivation will bring in soil from outside the

treated zone or mix the layers of treated and untreated soil; this should therefore be avoided unless a further steaming treatment is contemplated.

Work done to examine effects of steaming on *Tyrophagous* mites was inconclusive because mites were not extracted from soils from two of the sites. However, because of the observation of operating temperatures during steaming, it is highly likely that the soft-bodied mites would be killed by the steam.

The commercial appraisal of the machine was exhaustive, and produced cost data for two treatment times. Diesel usage was the major expense as would be expected, but was potentially balanced by the ability to leave the machine unmanned for long periods of time. Based on a steaming time of 5.3 min per station, the machine would treat one hectare in 70.6 hours. Treating for 8.0 min would increase this to 98.0 hours. The manufacturers have indicated that 8.0 min treatment would be unnecessary in many situations and on some soils less than half time may be appropriate, with consequent effects on cost per hectare.

In the course of the tests the machine was inspected by the Health and Safety Executive. Minor safety issues raised at that time have already been acted on by Regero, so there is no safety reason why growers requiring this technology should not import machines and start to use them immediately. Practical considerations would indicate that while 24 hour running is possible, in fields close to housing noise might be a problem. Further, although there may be situations where the machine may be left unattended for long periods. In fields which have footpaths or bridleways through them this might not be advisable

The steaming system used will have relevance to field salads and also a number of crops outside field vegetables. Potential for a high level of weed control is important for PYO crops such as strawberry and any one of a range of crops such as roses which still have a seed-bed growth stage. Simplification of the pathogen and weed burden may make it easier for growers to achieve control for several years following treatment. Coincidental control of weed borne diseases may also show benefits in later crop rotations, so it is obvious that the full benefit of a successful steam treatment will have considerable downstream effects.

- The project assessed the ability of a self propelled soil steaming machine to control soil-borne fungal pathogens, weed seeds and *Tyrophagous* mites.

- All the fungi were killed in surface layers of soil at three grower sites, including the native populations of *Pythium.*

- Temperature with depth in the soil was monitored in selected studies and showed that 100ºC was regularly achieved in those surface layers

- At greater depth, temperature increase was more moderate and the pathogens all survived.

- Native *Pythium* populations were monitored for three months after treatment and showed no, or minimal re-colonisation.

- Weed seed populations were also severely affected by treatment, and particularly for leaf salad crops, the concept of use of the steaming machine as the basis of zero herbicide production appears realistic.

- *Tyrophagous* mites were not detected in any soil samples from either of the two sites monitored. However, the soil temperatures generated in these tests indicate that such problem mites would be killed by this technology.

- A complete technical and financial appraisal of use of the machine was made and is given in this report.

- Although there was limited time to explore a wide range of treatments, the treatment cost generated compare favourably with those for methyl bromide, and have the potential for further reduction.

- The Regero machine was found to be easy to use, has been accepted as safe by the Health and Safety Executive, and has clearly been seen to have potential for introduction into leaf salad production and other areas of UK horticulture.

A - GENERAL INTRODUCTION

Heating soil to control pathogens, weeds and invertebrates has been practised since ancient times. In countries where solar radiation is sufficiently high exposing and turning soil in hot seasons was common practice (White, 1980). All treatments rely on the fact that most organisms are killed by periods of time at the temperature of pasteurisation (60ºC). Extensive work done since the 1890s has lead to a range of soil steaming options, most of which fell into disuse because of increases in fuel and labour costs in recent decades. This was also affected by the ready availability of chemical soil sterilants such as methyl bromide. Concern over the latter has prompted the present project which is based on one of several recently developed mobile soil steaming machines now commonly used in Europe.

The Regero machine (Figures 17 and 18, Annex 2) is designed for operation on raised beds, is self-mobile, and through computer controls may be set to treat particular bed lengths and then left to work. Steam is generated by a boiler fed by water from irrigation sources and treatment time is manipulated in accordance with soil type. The steam is applied under pressure beneath metal pans which are forced down into the loose soil of freshly worked beds. As a generality forcing steam down into soil is not easy. As this report will show, depth of penetration, and therefore kill of target organisms was strongly affected by soil type and moisture content. However, the machine was found to be effective and not difficult to use.

B - EXPERIMENTAL SECTION

PART 1 - Effects of soil steaming on five soil-borne pathogens and native *Pythium* populations at three grower sites.

Introduction

A wide range of fungal pathogens exist in agricultural soil and it was necessary to select a representative set of pathogens for this project. *Botrytis squamosa*, *Fusarium oxysporum* f.sp. *dianthi*, *Phytophthora cryptogea, Sclerotinia sclerotiorum* and *Verticillium dahliae* are respectively pathogens of onion, carnation, apple, lettuce and strawberry. All produce resistant survival structures which may be air dried and will survive for long periods in that state. Native *Pythium* populations at the different grower sites were also observed over time. Suitable methods of control for all these pathogens will be multi-spectrum. Multi-spectrum chemicals normally attack the basal metabolism of the pathogen. However as many metabolic pathways are shared even between kingdoms, including mammals, this provides a potential risk to human health during application and requires chemicals to disperse before planting can begin. The presently used control, methyl-bromide and its potential replacement 1,3-dichloropropene, applied with chloropicrin, are all toxic to humans and are therefore applied under polythene sheeting by specialised contractors. Steam is a safer more environmentally friendly option, which may be more attractive to consumers than the chemical alternative. Steam gives a non-selective kill of anything that cannot survive pasteurisation temperatures whilst being non-toxic to humans, and impacting less on the local environment. There is also no need to wait for chemicals to disperse.

Materials and methods

Production of the five pathogens

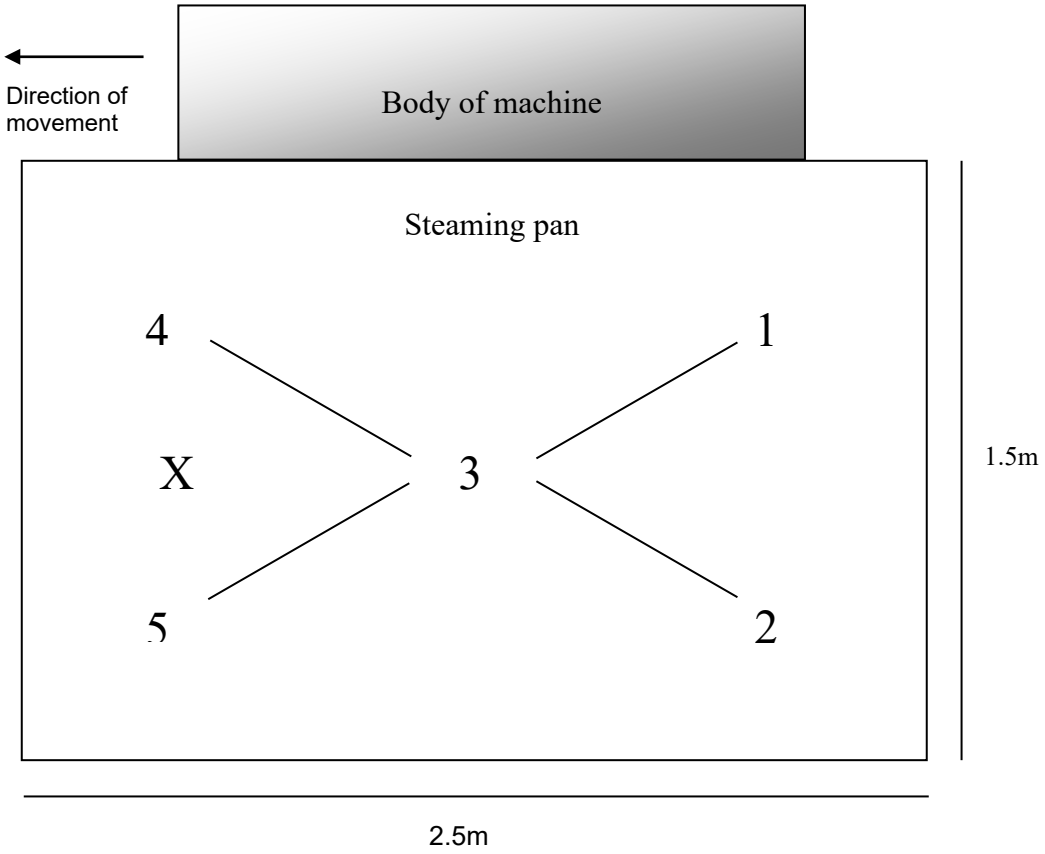
All pathogens were grown on an appropriate agar culture media before being inoculated onto the host material to be used during the trial. These were respectively salad onion, carnation leaf, grass blade, lettuce and strawberry petiole. Before inoculation host material was placed in distilled water and sterilised in an autoclave for 5 minutes at 5 psi. The material was then placed in a circle on a moist 70 mm filter paper disc in a petri dish and a piece of inoculum from the pathogen cultures was added centrally. When the inoculum had colonised the host material, and in the case of *Botrytis squamosa* and *Sclerotinia sclerotiorum* produced sclerotia, it was air-dried and sandwiched inside a folded 240 mm filter paper disc. The larger filter paper served as a barrier to potential sources of soil-borne contamination, whilst allowing steam to pass through with no impediment. A basic principle here was that the units of inoculum represented a massive amount of fungus in a highly resistant state for the steam to act on.

Burying and retrieval of captive inoculum

For the initial experiment, repeated four times at each of three growers, five sets of the five pathogens were buried at five depths 5, 10, 15, 20 and 25 cm. Pits were dug at the leading edge of the steaming pan, nearest the direction of movement of the steaming machine, X on Figure 1. Subsequent experiments involved looking at differences in steam penetration

between different areas under the steaming pan and different soil types. Two pathogens, *Fusarium oxysporum* f.sp. *dianthi* and *Phytophthora cryptogea* were chosen as most and least resilient to the treatment regime. These were buried together at 5 and 10 cm depths in five locations, described by a diagonal cross under the steaming pan, see Figure 1.

Figure 1: Pathogen burial locations under the steaming pan of the Regero soil steamer.



Numbers represent probe positions, and correlate to probe numbers given in the temperature curve graphs (see later). Steaming pan dimensions and the relative position of the machine was taken in account to orientate the steaming pan for each experiment.

After the steaming period, the soil was allowed to cool to < 60ºC before pathogens were excavated. Recovery of clean pathogen samples was aided by the larger 240 mm filter papers in which the sample was sandwiched. Each pathogen sample was placed into individually marked paper bags. All samples from the same depth were placed into individual plastic bags; this stopped cross contamination between samples from different depths; cross contamination between the different pathogens within each plastic bag could be easily ruled out due to the taxonomic differences between pathogens.

Regeneration of viable pathogens

Each 70 mm filter paper was plated out onto PDA, amended with the anti-bacterial agent rifamycin, and incubated at 20ºC. Petri dishes were examined for evidence of growth after 10 days.

Delta-T logging

Five of the six heat sensitive probes attached to a Delta-T "data logger" were buried alongside the pathogens; the other was always used as a randomly positioned soil surface control probe. Temperatures were recorded throughout the steaming period and afterwards until all probes had reached a temperature of < 60ºC.

Collection of native *Pythium* samples

Soil samples of approx. 100 g were collected between the five depths; 0-5, 5-10, 10-15, 15-20, and 20-25 cm. Soil was air dried in Petri dishes at room temperature, then sieved through a 1 mm 'Tygan' gauze to remove lumps, before dilution plating. For dilution plates, 0.1 g of soil was suspended in 10 ml 0.1 % water agar and vigorously shaken for 5 minutes. After being allowed to settle 1 ml aliquots of the resulting suspension were pipetted and spread onto plates of corn meal agar (CMA) amended with the anti-fungal agent pimaricin and the anti-bacterial agent rifamycin. Plates were incubated in the dark at 20ºC for 4 days. The water agar was removed by washing and colonies on plates counted and expressed as colony forming units (cfu) per gram dry weight of soil.

Soil moisture

At each grower four samples of soil were taken from the top 5 to 10 cm of soil before and after every steaming experiment. Approx. 50 g of soil was weighed into tinfoil cups, of known weight, and they were placed in a drying oven at a temperature of 110ºC overnight. The samples were then weighed again and percentage water content calculated.

Results

Delta-T logger results

Temperature curves plotted from temperature data at each site are shown in Figures 2 to 14. General features of the results are dealt with here, more specific items below.

As a general rule, temperature at the soil surface was seen to rise rapidly to 100ºC. At 5 cm depth, and to a lesser extent at 10 cm depth temperature also rose to 100ºC within minutes. With increasing depth, the time taken for any increase was longer and the temperature achieved lower until at 25 cm there was commonly no change throughout the treatment period.

Tests with probes placed at different sites under the steaming pan on the soil surface, then at 5 or 10 cm depth showed little temperature variation. This would indicate that treatment should generally be even across the beds.

In the surface layers of soil, an unexpected feature of the treatment was the time taken for the temperature to fall below 60ºC. More than one hour was common, and at some sites the process took over two hours. We mention that digging into soil with bare hands shortly after the steamer has passed is a painful experience.

Effects on the five pathogens

For reasons of commercial confidentiality the collaborating growers are identified only by numbers.

Results for pathogen recovery are shown in Tables 1 and 2. Table 1 shows that none of the five pathogens survived the steam treatment at 5 cm depth in any of the soils. At Grower 1 *Fusarium oxysporum* did survive at a depth of 10 cm in replicates 1 and 4. Temperature data for replicate 4, Figure 3, shows that the 10 cm probe did not reach 60ºC during the experiment. All pathogens survived at lower depths. For this reason it was decided that pathogens would not be buried lower than 20 cm during experiments at Growers 2 and 3.

At Grower 2 all pathogens were killed down to a depth of 10 cm with the exception of *Fusarium oxysporum* in replicate 1; Figure 8 shows that for this replicate the soil temperature did not reach 60ºC at the 10 cm depth.

At Grower 3 all pathogens were killed down to a depth of 15 cm with the exception of *Fusarium oxysporum* and *Sclerotinia sclerotiorum* in replicate 4.

Effects of soil type

Two different soil types were investigated at Grower 1; light clay and heavy aggregate clay. The pathogens *Fusarium oxysporum* f.sp. *dianthi* and *Phytophthora cryptogea* were buried, with temperature probes, at 5 and 10 cm depths (see Methods). The light clay soil gave even temperature curves for the 5 locations under the steaming pan at both depths (Figures 4 and 5). The only pathogen survival observed was *Fusarium oxysporum* at a depth of 10 cm at position 1 (Table 2).

For the heavy clay, temperatures between the five locations under the steaming pan varied considerably during the cool down period, at both 5 and 10 cm depths (Figures 6 and 7). The time taken to reach 60ºC was considerably less for the heavy clay soil and temperatures fell rapidly from 100ºC as soon as the steamer had moved on; almost twice as fast compared to the light clay. At the 10 cm depth probe 3 is conspicuous, as soil temperature around the probe did not get higher than 34.5ºC. *Fusarium oxysporum* was recovered from location 1 at 5 cm, and locations 2 and 3 at 10 cm. No *Phytophthora cryptogea* was recovered from any site in either soil type.

Effect on native *Pythium* populations

The naturally occurring *Pythium* populations, represented by the unsteamed controls, varied between the three growers and over time (Table 3). Populations on steamed areas at Grower 1 were killed within the top 0-5 cm of soil; no re-colonisation was observed during the three month trial. At lower levels no initial kill was observed; however the first observation may have been anomalous as later samples showed 90 to 99 % kill in the 5-10 cm zone. The control population soil profile maintained a classic inverted pyramid. However the numbers of colony forming units (cfu) fell over the three months; in the top layer, 0-5 cm, the starting number of 533 cfu at time zero fell to 200 cfu at three months. At Grower 2 a similar trend was observed at 0-5 and 5-10 cm for steamed plots, although the control populations, and those below 10 cm in steamed plots, remained at a constant level throughout the trial. Deeper steam penetration was observed at Grower 3 resulting in kill of *Pythium* down to 10 cm, with no re-colonisation in the first 1.5 months; the three month score showed a slight increase in cfu in the 5-10 cm zone. At 10-15 cm an initial kill of approximately 75 % was observed, this was not maintained. Natural *Pythium* populations were initially very low at Grower 3 but fluctuated over the three month trial.

Composition of Native *Pythium* populations

Pythium isolations at Grower 1 were dominated by the HS (hyphal swelling group) and *Pythium sylvaticum*. Also present were single isolates of *P. mamillatum*, *P. paroecandrum*, *P. ultimum* and *P. oligandrum*. For Grower 2 the HS group and P. *sylvaticum* were again most common with *P. ultimum* also common and fewer observations of *P. oligandrum, P. paroecandrum* and *P. irregulare*. At Grower 3, the HS group, *P. sylvaticum* and *P. ultimum* were equally common, with a small number of isolates of *P. irregulare*. This basically confirms the dominance in such soils of the common fast-growing species of *Pythium* and the presence at two growers of the mycoparasite *P. oligandrum*. That the parasitic species did not substantially re-colonise the treated soil within the three months trial period is somewhat unexpected, but a good feature of the steaming treatment. Survival of *P. oligandrum* below the treatment depth and the possibility that it could re-colonise treated soil could be an unexpected bonus.

Soil moisture

Initial soil moisture content varied considerably between the growers; Grower 1 had the highest at 17.1 %, Grower 3 the lowest at 8.4 %. After the Regero Steaming machine had been used the moisture content of the three soils increased by 2.2 % at Growers 1 and 2 and by 1.6 % at grower 3 (Figure 15). The comparison study between light and heavy clay soils at Grower 1, Figure 16, showed that the heavy clay soil took up only 0.7 % additional water compared to the 2.5 % additional water taken up by the light clay.

Discussion

The “Regero” soil steaming machine effectively killed all pathogens in the trials in the top 5 cm of soil and significantly reduced pathogen burden up to a depth of 15 cm depending on the soil type and condition. Steaming was most efficient on well-drained sandy soils where steam could penetrate to greater depths. Heavy clay lumps may harbour pathogens in an environment which steam cannot penetrate; however it is unlikely that the presently used chemical treatments, mentioned above, would have any better effect. Longer steaming periods allow deeper penetration; an ideal balance between pathogen kill, and, fuel and time consumption may need further investigation. Re-colonisation of *Pythium* species at the three growers was almost non-existent suggesting long term pathogen control may be achieved by this method.

PART 2 - Weed studies

Introduction

In an arable field, the soil down to plough depth may contain anything from less than 25 to over 25,000 viable weed seeds per m^2 with a median of around 4,000, equivalent to 40 million weed seeds per ha. Seedbed preparations and other soil disturbances stimulate weed seed germination and this is followed by a flush of weed seedling emergence. For a variety of reasons less than 5 % of the seeds present in soil are likely to germinate after soil cultivation. This means that even if there is complete control of the weeds that emerge in the current crop, sufficient ungerminated seeds will remain to give problems in future crops for many years. The potential advantage of using soil steaming for weed control is that all the viable weed seeds, including dormant ones, within the treated soil layer will be killed. There is no residual effect of treatment, so no delay in crop establishment and no problem with replanting if crop failure should occur for any reason. However, because there is no residual effect, any weeds that are not controlled or that develop from seeds introduced after steaming or from outside the treated zone will be able to grow unchecked and may benefit from the absence of other weeds.

It is well known that weed seeds in greenhouse soils are killed by steam sterilisation. In the field, however, not all the soil can be steamed and there is a limit to how deep it is economic to treat the soil. Although weed seeds are distributed throughout the plough depth, few weed species can emerge from deep burial, and in general the bigger the seed the greater the depth of emergence. The depth of emergence of some common annual weeds is given in Table 4. Only the seedlings of a few species are able to emerge from depths of 60-120 mm or more, and the field emergence of some weed species is limited to just the surface 20-30 mm of soil. Even with weeds that can emerge from deeper in the soil, well over 98 % of all weed seedlings emerge from depths of less than 50 mm (Chancellor, 1964). After soil cultivation, some seeds below the optimum depth of emergence may germinate if conditions are otherwise favourable and then fail to emerge. However most will remain dormant until the next series of cultivations move them nearer to the soil surface.

Perennial weeds develop from vegetative organs in the soil and are likely to emerge from much greater depths than annual weeds. While some like Common couch (*Elytrigia repens*), have relatively shallow rhizomes the vegetative organs of others, like Creeping thistle (*Cirsium arvense*) and Field bindweed (*Convolvulus arvensis)*, are buried deep in the soil. It is unlikely that a single steaming will control these deep seated weeds.

Materials and Methods

Weed seedbank estimation

Before steaming began, soil samples were taken to provide a rough estimate of the seed load and the weed species present at the three growers. The steaming treatments began relatively late in the season when, for a variety of reasons, weed emergence can be less than earlier in the year. This might give a false impression of the potential weed problems and levels of control at the different growers. The weed seeds were extracted from four 200 g sub-samples of soil from each grower by a system of washing, sieving and filtering based on the methods of Roberts & Ricketts (1979). The number of apparently viable weed seeds and intact seed coats recovered was recorded for each species present

Field steaming

The effect of field steaming on weed development was investigated in three trials at Grower 1, one trial at Grower 2 and two trials at Grower 3. In each trial at the three growers, a 30 m length of bed was steamed and left undrilled while a similar length of untreated bed was left for comparison; neither bed was cropped. The first weed assessments were made once the main flush of weed emergence had occurred. Each bed was divided into three sub-plots and the weeds in 12 random quadrats (0.5 x 0.5 m) recorded from the flat bed surface of each sub-plot. The percentage cover of the weeds in the quadrats was also recorded. A second assessment of the weeds was made six weeks later to determine whether further emergence had occurred on the steamed strip due to the introduction of wind-blown seeds or to emergence from soil below the treated layer. Where vegetation cover was light, all the weeds on the treated and untreated strips were recorded as before. In the trials where there was virtually complete plant cover on the untreated strip, only the additional seedlings on the steamed bed were recorded.

At the time of the first weed assessment, the beds on the earliest trial at each grower were sampled to 25 cm for soil pathogen determinations. When the second weed assessment was made, weed emergence was recorded in a 0.5 X 0.5 m quadrat centred on each of the four areas of soil disturbance on the steamed strips only.

Results

Weed seedbank estimation

The results of the weed seed estimates from the soil samples taken at each grower are given in Table 5. The viable seed numbers at Grower 1 were about average for horticultural land,

the numbers at Grower 2 were very high and Grower 3 had very low weed seed numbers. At the two weedier sites, Shepherd's purse (*Capsella bursa pastoris*) was the main weed. Annual nettle (*Urtica urens*) and Fat hen (*Chenopodium album*) were present in large numbers at Grower 2, the weediest site. It must be stressed that these estimates of viable weed seed numbers were from limited soil samples and were intended only to give an indication of the weed seedbanks at the three growers. The numbers in brackets in the Table refer to the seed coats found in the samples. While these would not contribute to a future weed flora they give an indication of previous weed populations. Although Grower 3 now has low weed numbers apparently, Fat hen (*C. album*) could have been a problem weed in the past.

Field steaming

First assessments

Table 6 shows the mean weeds per metre square on the untreated control and steamed beds in the three trials at Grower 1. In trial 1, Shepherds purse (*C. bursa pastoris)* was the most frequent weed and made up three quarters of the dense vegetation cover on the untreated control strip. The steaming treatment gave over 95 % weed control on the main bed area (Fig 19, Annexe 3). Shepherds purse (*C. bursa pastoris* was the main survivor on the surface of the steamed bed together with odd seedlings of Groundsel (*Senecio vulgaris*) and Sowthistle (*Sonchus* spp.) However, while the recorded area on the steamed bed was relatively weed-free in comparison to the untreated bed there were many weeds remaining on the shoulders of the bed and in the wheelings between beds.

At the two later established trials at Grower 1, weed numbers were lower than in the earlier trial on the untreated bed (Table 6). Vegetation cover was light and weed development was not complete. The main weed in trial 2 was Annual nettle (*U. urens*). In trial 3, few weeds had emerged, possibly due to dry soil conditions, and there was no dominant species. Weed control on the steamed beds in trials 2 and 3 appeared to be complete at the first assessment. There were weeds present in the wheelings between the beds (Figure 20, Annex 3).

In the single trial at Grower 2, the weediest site, Shepherd's purse (*C. bursa pastoris*), Annual nettle (*U urens*), and Gallant Soldier (*Galinsoga parviflora*) were the main weeds with Sun spurge (*Euphorbia helioscopa*) and Green nightshade (*Solanum physalifolium*) also present (Table 7). Vegetation cover on the untreated beds was so dense that the weed numbers may be an underestimate due to self-thinning of seedlings at an early stage in emergence. Nevertheless, steaming achieved over 98 % control of the weeds with just the odd survivor on the treated bed surface. Shepherd's purse (*C. bursa pastoris* was the main survivor but no species appeared to be especially tolerant of treatment (Figure 19, Annex 3). There were many weeds remaining on the shoulders of the bed and in the wheelings.

The results of the initial weed counts in the two trials at Grower 3, the least weedy site based on the soil samples, are given in Table 8. There were very few weed seedlings recorded even on the untreated beds; most of the seedlings recorded were of volunteer crops. Annual meadow-grass (*Poa annua*) and clover (*Trifolium* spp.) were the main weeds present on the control beds. Weed control with steaming was between 80 and 90 % at the two sites but clover (*Trifolium* spp.) appeared to survive treatment.

Second assessments

At Grower 1, weed cover was too dense on the untreated strip of trial 1 to allow further weed emergence to occur. A few new seedlings had appeared on the steamed strip though and these were recorded (Table 9). The new weeds were generally species with wind dispersed seeds like Groundsel (*S. vulgaris*), Sowthistle (*Sonchus* spp.) and Willow herb (*Epilobium* spp.). Where the soil on the steamed strip had been disturbed by sampling down to 25 cm for *Pythium* determinations, a greater number of weed seedlings had emerged (Table 9). Mayweed (*Matricaria* spp.) and Groundsel (*S. vulgaris*) were the main species recorded. Some of the groundsel (*S. vulgaris*) could have germinated from wind blown seed trapped on the rough soil surface but the mayweed (*Matricaria* spp.) would have come from seed brought up from below the steam treated layer of soil.

In trials 2 and 3 at Grower 1, the weed population had increased and both the number and percentage ground cover of the weeds on the steamed and untreated strips were recorded again (Table 10). Weed numbers were greater than at the first assessment but Annual nettle (*U. urens*) was still the main species present in trial 2. On the steamed bed, Willow herb (*Epilobium* spp.) was the most frequent weed but weed control remained effective and number and percent cover of weeds were low. In trial 3, Annual meadow grass (*Poa annua*) had become the most frequent weed but contributed relatively little to the thin vegetation cover. On the treated bed, weed numbers remained very low.

At Grower 2, weed cover was again too dense on the untreated strip of the single trial to allow further weed emergence to occur. A few new seedlings had appeared on the steamed strip and these were noted (Table 11). Where the soil sampling had disturbed the soil on the steamed strip, a flush of weed seedlings had occurred (Table 11). Shepherd's purse (*C. bursa pastoris*) and Gallant soldiers (*G. parviflora*) were the main species present.

The vegetation cover was not complete even on the untreated strips of the two trials at Grower 3, and both the number and percentage ground cover of the weeds on the steamed and untreated strips was recorded again (Table 12). There was little change in weed number or species composition in either trial but vegetation cover had increased due mainly to the growth of the volunteer crop seedlings. In the disturbed sample areas of the steamed strip in trial 1, a few additional seedlings had emerged but not many compared with the other sites (Table 13).

Discussion

The trial results show that over the treated bed surface steaming is very effective in controlling weed emergence. Few weeds emerged after treatment at any of the growers despite both the seedbank estimates and the weed seedlings present on the untreated strips confirming that there were high potential weed populations at two of the three growers. While the steaming treatments appeared to have killed the seeds in the surface layers of soil, it was evident from the additional weed emergence where soil sampling had taken place that weed seeds had survived below the treated layer.

There was a suspicion in trial 1 at Grower 1 that some surviving weeds on the treated bed were associated with the edges of the steaming pans. This may have been pure chance or may have been due to unfamiliarity with the machine and its operations in the first trial. There was no evidence of this happening in subsequent trials. The majority of the weed seedlings that survived on the steamed bed are likely to have germinated from seeds blown or been carried in from the untreated areas after steaming. In general they were less well developed than weed plants on the untreated bed suggesting a later date of germination. Most were shallowly emerging species with small thin coated seeds e.g. Shepherd's purse (*C. bursa pastoris*) that would not survive steaming or emerge from below the depth of the treated zone. The exception was Clover (*Trifolium* spp.) which also emerges only from relatively shallow soil layers but has hard-coated seeds that could survive the steaming process; it is known that clover seed survives after methyl bromide treatment of field soil. Whatever the origin, the odd surviving weed is unlikely to be a problem in a dense crop like spinach. Unlike in the uncropped treated beds in these trials, weed seedlings from wind-blown seeds would have difficulty becoming established in a growing crop. However, in a more open crop, surviving weeds could thrive and proliferate causing a shift in the species composition of the soil seedbank to a weed flora that would tolerate steaming treatment.

The poor weed control at the edges of the bed and in the wheelings was the main problem encountered in the trials and needs to be addressed if steaming is to be fully effective. Even if the weeds do not affect crop yield, they will be a source of future weed seeds. In addition, the soil in these weedy areas will contain viable seeds that would be moved into the treated soil areas during cultivation. The soil below the treated zone will also contains viable seeds that could germinate if brought nearer to the soil surface by cultivating below the steamed layer of soil.

PART 3 - *Tyrophagous* mites

Introduction

One of the growers collaborating in this project had previously contacted HRI Wellesbourne with respect to a mite problem in salad crops. Based on previous examinations of mite samples from the beet crops the mites were classified as belonging to the group known as Astigmatic mites, which include well known, albeit infrequent, plant pest species in the genus *Tyrophagous*. It was decided to investigate the effects of soil steaming on such mites.

Materials and methods

Samples of soil were taken initially after the steaming and then at one and a half and three months. Four soil samples were taken, randomly spaced within the beds, on each occasion from the top 5 cm of the soil for both treated and untreated soil. Soil samples were placed in Tulgran funnels suspended over beakers of alcohol; the mites burrow deeper into the soil in response to the heat and as the soil dries where they then fall into alcohol. Mites were then to be counted and classified under a microscope.

Results

No mites were extracted from any of the samples.

Discussion

At the first two growers there were no standing crops, and at the first and third growers there were considered to be mite problems. The lack of organic matter as a food source for mites at the first two sites suggests that these mites could not persist for very long in the soil without an additional food source. The fine texture of the soil would also suggest that it is prone to drying out. Astigmatic mites are soft bodied mites that require high relative humidities and are very susceptible to dry conditions. The mites have a distinctive and specialised phoretic "dispersal" phase known as a hypopus which develop in adverse environmental conditions. Hypopi quickly disperse by attaching themselves to other animals (arthropods and vertebrates). Both these factors would indicate that in the absence of plants the mites probably do not persist and either disperse rapidly or die out. The fine texture of the soil would make the mites very susceptible to the soil sterilisation in operation. However, the mites may easily recolonise the area once plant material has been re-established in the soil. A pattern of high populations, when plants are present, followed by rapid decline to zero populations would not be unusual in this circumstance.

PART 4 - Commercial appraisal of the Regero machine

Introduction

One grower provided a worker to accompany the machine to all trial sites, to run it and to log all aspects of its use during the trials. In addition to day-to-day aspects of the running of the machine, problems encountered were recorded, and below we give as comprehensive an account of working with the machine as is possible.

Materials and methods

The machine is shown in Figures 17 and 18 Annexe 2). By the use of three steaming pans the machine treats a central bed plus one to the left and one to the right. Guiding skids which sit in the wheelings ensure forward motion in relation to the beds, and once set in motion the machine may be left unattended.

Steaming process

Water is fed to the machine through an umbilical cord, or hose, at pressures between 3.5 and 6 bars, the supply being controlled electronically via the boiler level switch. The water first enters a rear pre-heating cylinder, then flows to a front pre-heating cylinder and then into the main boiler. Steam from the boiler is piped back past the burners to increase its temperature, then through a hydraulic valve which ensures that the steaming process occurs only when the

steam pans are properly in position. Working temperature naturally fluctuates between 100 and 160ºC steam is forced under pressure through a central pipe on each steam pan and is deflected laterally by a metal plate. To prevent escape of steam, the steam pans are held in contact with the soil under a hydraulic pressure of approx. 70 bars. This may be varied according to soil type.

Automatic movement and steering process

The steaming machine is mounted on four wheels pre-set in the factory to appropriate bed width. When set to steam, the machine embeds the three steaming pans in the soil, and generated steam is released for the period of time set by the operator. The operator can also set the number of cycles the machine should perform, that being appropriate to the bed length to be treated. At the end of one cycle of steaming the pans are raised and the machine moves forwards under hydraulic pressure approx. 2.5 m in 31.5 sec, this being regulated by a floating wheel at the rear. The pans are the lowered and the steaming process repeated. At each operation, there is a small overlap of the pans with the previously steamed area to ensure that no soil on the bed surface is left untreated.

Burner process

As with many functions on the machine, the burner can only operate when there is adequate water in the boiler. Diesel fuel is provided from a 1500 l tank. In operation, air is taken in from an elevated chimney 1.5 m above the bed (to avoid taking in steam), generated heat is blown along the length of the boiler and is exhausted above it.

Automatic stopping

When operating in automatic mode there are two ways of stopping the machine. As mentioned above, it may be pre-set to cover a certain distance, after which it will stop working. Alternatively sturdy metal rods placed in the centre bed may trip the emergency stop cable fitted across the front of the machine.

Other devices will first stop the machine working and then turn it off. These are:-

1. Rain gauge, which senses when rainfall has reached a level that might impair the steaming process.

2. Water supply gauge which halts forward movement and turns the machine off after 30 min.

3. If the measure wheel is not down, the machine will only travel 20 m before stopping.

4. Insufficient steam pressure in the boiler causes shutdown.

5. Lack of diesel for the burner causes shutdown.

Objectives of the assessments

Three main areas were considered:-

1. To assess running costs – diesel usage, water usage, labour and capital cost implications.

2. To assess work rate – running hours/ha, down time and factors affecting work rate.

3. To assess potential commercial usage – practicality of the machine and breakdown and repair costs.

Results and Discussion

Running costs

Diesel usage

a) Lambadini motor, a low revving motor which runs the generator

1 litre/h @ 11 pence/litre

Service required every 250 h

Filters @ £10 each x 2 - £20
4 litres oil @ 52 pence/litre - £2.08

b) Burner

The amount of diesel used can be affected in three ways

Temperature of water supply
Temperature of the air entering the burner
Weather as with humidity, cloud, frost

Diesel usage approx. 53.3 litres/h (range 50 – 56 litres)

53.3 litres/h @ 11 pence/litre - £5.86/h

Water usage

a) To fill the machine requires 550 litres

550 litres @ 0.058 pence/ litre – 32 pence/filling

b) Water usage when running – 528 litres/h

528litres @ 0.058 pence/l – 31 pence/h

Water usage while the machine is running can be affected by the cycle time, the longer the cycle the more water is used.

Labour

As stated above, once the machine is properly set and working in good environmental conditions it may be left unattended for long periods of time. It was our experience that regular minor jobs required presence of an operator. They were:-

Time to fill with water – 15 – 40 mins

Heating-up time – 15 mins

Turning time – the machine is extremely slow under its own power, and this could be up to 30 mins, depending on the area available for turning

Breakdowns are considered in Annexe **1**

Servicing

Lambadini motor servicing is an extremely simple job which could be done by anyone with some experience.

Diesel filters are of two types, one coarse and in line, easily removable, the other a fine filter in the burner and quite accessible. The use of clean diesel is of paramount importance.

Water removal from the steam pipe via drainage taps is essential to ensure maintenance of high steam temperature.

Steam pan pressure to prevent escape of steam from soil can be adjusted quite simply with a screwdriver, and achieving the correct level is easily judged.

Soil temperature after steaming should be routinely checked with the temperature probe supplied with the machine. Throughout this exercise this was based on achieving 80ºC at 10 cm depth.

Work rate

This was derived by the formula:-

$$B/A = C \times D = E/60 = F/60 = G$$

Where:-

A is the area of soil steamed at one cycle – approx. 14 m^2

B is 1 ha – ie 10,000 m^2

C = B/A

D is the number of seconds per cycle + 31.5 seconds movement time

E = C x D

F = E/60 – the time for treating 1 ha with continuous working

In the present work the fastest cycle time used was 5.3 min:-

10,000/14.22 = 703.2 x 361.5 = 245219/60 = 4236.99 = **70.6 hours/ha**

The slowest cycle time used was 8.0 min:-

10,000/14,5 = 689.7 x 511.5 = 35279/60 = 5879.3/60 = **98.0 hours/ha**

These calculations consider a hectare including tractor wheelings. To derive the cost for treatment of a true hectare, add a factor of + 17 %.

Representative costs to the grower to fund normal running of the machine were calculated to be £11.07 per hour On this basis, the cost to treat 1 ha would vary between £871.52 and 996.30, considerably less were treatment time cut to 3 min. This would obviously be soil type and condition dependent. By calculating on the machine possibly working for half of each year (3744 hours) an annual running cost in the area of £41,446 would result in relation to steaming of 40 to 50 hectares.

Capital cost would vary with the specification of machine purchased and it would not be reasonable here to attempt a precise costing.

Factors found to affect work rate

Soil type had an observable effect in that temperature rose more slowly in heavy soils than in light soils. The same was true of soil with high moisture content as opposed to low moisture content. With light dry soil there was a tendency for the steam to blow out channels through which it easily escaped. Bed preparation close to the time of steaming affected both the performance of the steaming pans in preventing escape of steam, and the penetration of steam through the soil. However, the British weather proved to be of major importance in that only three weeks work output was achieved in the five weeks available. Although six days were lost due to breakdown, of those only two were workable.

Although speed of working was not great, because when all is going well the machine can be run for 24 hours per day, area treated is not unreasonable. The manufacturers have indicated that when soil type and conditions are optimum, a cycle time of only three minutes may well be sufficient. This would clearly bring down the time to treat a hectare to around 40 hours, with consequent reducing effects on all inputs.

Here, the machine worked at three growers with soil preparation with different single bed formers, all of which gave slightly different bed conformations each requiring adjustment of the steaming pans. It is known the machines work more effectively when tailored to a specific triple bed former. Further, the steaming pans are tailor made to fit the beds to be used on individual farms, and obviously for a machine operating in one organisation this would remove one source of delay.

General comments

The machine was easy to operate and service. With a steady and reliable source of water it really can be left to work unattended.

One concern was the fluctuation in working temperature between 100 and 150ºC and would have an effect on work rate through condensation building up in steam pipes, with consequent need to drain them.

The above trials were obviously conducted in what was a very wet summer, and there are implications for usage of the machine, particularly on medium to heavy soils.

Grower feedback on crops grown after treatment

Grower 1 cropped once with baby leaf spinach which received two irrigations in the week after drilling. No herbicide was applied to the crop. Crop on treated beds was earlier by 3 – 4 days than that from untreated soil. Treated crop was greener in appearance and softer to the touch than that from untreated soil. These effects were ascribed to possible nutrient release from the steaming. Growth was very even apart from where the steaming pans overlapped where plants showed slightly poorer growth. Without taking crop yield data, it was felt that the treatment did not give a noticeable yield increase. Weeds were no more or less than levels on non-steamed beds which had received herbicide.

Grower 2 cropped once with leaf spinach and did not apply herbicide to the crop. On the longer crop, there was no apparent beneficial effect of the treatment apart from lack of weeds in the beds. However, weeds in the wheelings and on the bed shoulders grew unchecked and both caused an immediate problem for harvesting to the bed edges, and were shedding seed at the point of harvest. This clearly indicates that with other than the very short-term crops, it will be necessary to devise a system for applying herbicide in the wheelings and on the bed shoulders.

Grower 3 Treated beds were cropped with lambs lettuce. The crop established well and very evenly. There were very few weeds in the treated beds, mostly volunteer red mustard from a previous crop. Subsequent growth on treated beds was possibly 2 – 3 days earlier and a little more uniform than on untreated beds. At point of harvest weed numbers remained very low and presented no problems.

C - OVERALL DISCUSSION

The Regero soil steaming machine was thoroughly assessed at different grower sites with a number of soil-borne fungi, including native *Pythium* populations, and weeds. While attempts to measure effects of treatment on *Tyrophagous* mites were inconclusive, temperature data suggests that such mites would be killed.

Although relatively extensive, these tests have investigated relatively few of the totality of effects the steam treatment would have on both harmful or beneficial organisms in soil. Compared with methyl bromide, the effects of steam did not penetrate soil to a great depth. This means that many organisms would survive in areas where pasteurisation temperatures were not reached or maintained. Given potentially lower costs and the fact that subsequent crops would not contain high bromide residues, this treatment appears to have advantages over methyl bromide. Further, the short treatment time for any particular piece of soil contrasts completely with static steaming methods where treatment times around the hour may be used. It would therefore be predictable that steam delivered in the present way would be less environmentally damaging than either a highly toxic fumigant or lengthy static steaming.

It is predictable that a wide range of fungi would be killed by the present treaments, and benefits across a wide range of horticultural crops could be achieved. It is known that the manufacturers have developed machines for use in protected horticulture, and subject to efficacy testing, they could be beneficial in that area.

Specifically for weed control, the technology appears to present a good option for leaf salad growers. If they are under pressure for production without herbicides then this would suffice. The method is also well suited for their production methods, working on the raised beds they drill into, and giving them the option to drill as soon as the soil has cooled down. That seeds survive in wheelings and below the treatment depth is seen only as a short-term problem. In discussions with the present growers, it was clear that they could visualise taking the benefit from treatment of one set of beds, cultivate and raise new beds then re-treat. Seen in the context of cropping over a number of years the problem of weeds from the accumulated seed bank would inevitably be reduced.

The present growers were all involved in extensive production, moving round a number of fields. Within the industry there are large numbers of small growers, or those who are limited because of urban development, who may be close to monoculture growing. For these growers, to have access to such a machine to clean up weedy land from time-to-time could be valuable. Providing the economics could be made favourable one might imagine such growers using the machine before every crop.

D - OVERALL CONCLUSIONS

1. The machine assessed above has been found to be effective in its purpose, and although conditions for some trials were not ideal, an acceptable level of treatment was always achieved.
2. Major effects on soil-borne fungi and weed seeds were demonstrated, and theoretically the treatments would be expected to kill *Tyrophagous* mites.

3. Results of trials were consistent with the exercises monitoring soil temperatures, and most and least favourable soil types for treatment were identified.
4. Although soil steaming may be seen to be an extremely rigorous treatment, the way this system has been developed, the short treatments cause minimum disruption to soil organisms, and could be used to maintain good mixed soil microflora.
5. The tests in these trials were chosen to ensure that effects of treatments were measurable. It is clear that shorter treatment times may be possible, and that would reduce cost/ha compared with our analysis.
6. Cost benefit analyses indicate that the machine could be purchased and over a period of years operated less expensively than continuing with methyl bromide treatments.

E - ACKNOWLEDGEMENTS

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F - REFERENCES

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Annexe 1

Breakdown and repair costs

In the course of the trials the generator needed replacing – cost £16900

One solenoid failed to work and disabled the machine for a day – cost of solenoid £83. As for other solenoids and fuses, a sensible precaution would be always to have spares available.

Absence of seals to injector nozzles in the burner resulted in a diesel leak – no cost implication, but a cause of lost working time

Not the responsibility of Regero, but essential information for potential users of the machine. Water hoses must be of high quality as they are subject to cuts and abrasion. Hose joiners should always be available.