insecticides will remain an important component of pest control for many years to come.

Trends in pest control now are in the direction of integrated pest management. Because a single line of attack is often unsuccessful in the long term, methods of integrating two or more compatible techniques show promise for improvement in plant protection over the long term. Integrated pest management programs which have been developed thus far rely heavily on a biological control component, but chemical insecticides are used when necessary, and in a way least likely to disrupt the gains which have been made by biological control.

AERATED STEAM TREATMENT OF NURSERY SOILS

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Growers have become increasingly interested in soil treatment and in pathogen-free stock as they have realized that the ultimate sources of disease organisms are the soil (including water and nonliving organic matter) and living plants. Soil treatment may be accomplished by chemical fumigation or by steam. Destruction of microorganisms has been the objective of such treatments since they started in 1880-90, and recommendations have emphasized overkill rather than minimal effective dosage. There is now a marked trend toward minimal treatments and toward fumigants selectively toxic to pathogens so as to avoid creating a biological vacuum dangerously subject to reinvasion by pathogens, and so as to decrease formation of toxins injurious to plants.

Commercial soil steaming to control diseases and insects was begun in 1893. but the methods remained empirical for 60 years, with little scientific study or grower inventiveness. Critical investigations were published in England, Norway, and California in 1954-60. The studies on aerated steam at the first two places were made by engineers in an effort to reduce fuel consumption. Our California studies were aimed at avoiding the creation of a biological vacuum and production of phytotoxins. It has been known for 35 years that moist heat of 140°F for 30 minutes will destroy plant pathogens (except tobacco mosaic virus); treatment at higher temperatures therefore wastes energy and is biologically undesirable. Plant pathogens are more sensitive to heat than are many saprophytic microorganisms. Treatment at a temperature just sufficient to kill pathogens will leave a substantial microflora that will compete with and be antagonistic to any pathogen later accidentally introduced. A form of biological control of plant pathogens is thus provided.

Creation of a similar effect by fumigants and other chemicals now used has proved impractical. Highly specific chemicals are subject to the considerable risk of microorganisms developing resistance to them; such resistance to heat, which affects large metabolic targets, has not developed. A volatile fumigant injected into soil diffuses outward in expanding spheres, but, since it is sorbed by the soil, its concentration decreases progressively out from the point of injection. Treatment, therefore, is characteristically nonuniform through the soil mass, with overkill at the point of injection and undertreatment at the outer points. By comparison, the temperature of soil treated with steam or aerated steam is uniform throughout. The steam condenses on the soil until it reaches the injection temperature, then passes by and condenses on the next cool soil. BTU are released only at the point to be heated. The only variable is the time required for steam to permeate the soil, and with proper equipment and adequate steam flow this can be very short. Aerated steam is thus better suited to controlled manipulation of soil microflora than are chemicals.

Movement of Aerated Steam through Soil. Soil steaming is essentially the transfer of heat from a boiler to the soil. Aerated steam diffuses through the continuous labyrinthine pores of the soil to particles colder than itself, where the steam component condenses. It therefore moves as an advancing front (treatment temperature on one side and unheated soil on the other) that varies from an inch or less in width (with efficient high steam-flow rate or proximity to the input) to several inches wide (with low steam-flow rate or greater distance from the steam input). In this zone of heating the aerated steam mingles with the pore air, producing a mixture ever richer in steam as the temperature rises. The displaced pore air and the air from the spent aerated steam are pushed out, imparting their heat to soil particles as they pass out of the soil. A ready escape for this expelled air must be provided or the aerated steam will not penetrate, and the soil will not be heated.

Ground beds, therefore, usually cannot be effectively steamed by surface application because of the excessive friction to the downward and outward movement of the displaced air through the compacted soil beneath the bed and in the walks. By comparison, there is relatively unimpeded outflow of air through the bottom of a raised bench, and porous soil 10-12 inches deep may be readily steamed.

Since aerated steam penetrates very poorly into compacted or low-porosity soil, thorough cultivation to the desired treatment depth is required. For the same reason, clods should be screened from the soil or broken up by cultivation. Soil moisture beyond that required for good planting tilth decreases efficiency because of the increased heat capacity and diminished pore size. Dry soil should not be treated since weed seeds and spores of plant pathogens are more resistant to heat when they are dry than when moist.

Application of aerated steam from the bottom of the container is best done through buried pipes or an enclosed space (plenum) with a perforated upper plate on which the soil rests. To avoid restricting the air outflow, a tight tarp cover should not be placed over the surface until the soil air is displaced (i.e., until the soil has reached the desired temperature).

There is now a marked trend toward application of aerated steam to soil through a plenum at the top in order to reduce "blowouts" (eruptions of steam through chimneys of fluidized soil that bleed steam from the rest of the treatment area). Steam follows the path of least resistance. Downward "blowouts" tend to seal themselves with loose soil. Steam injected into a top or basal plenum moves along the walls of the treater faster than at the center. This tendency is diminished when the soil layer is no deeper than 24 inches, when a porous soil mix is used, and by using a relatively high steam flow rate.

Mixing air with steam dilutes it and lowers its temperature to any desired level. The ratio of air to steam at 212°F is 0:1 by weight; at 180°F it is 1.5:1; at 160°F it is 3.3: 1; and at 140°F it is 6.5:1. The lower the temperature desired, the greater is the amount of air required, and the poorer the mixture in heat content. The old steam treatments at 212°F/30 minutes had a very large margin (72°F) of safety, and even relatively careless treatment usually was effective. Even if the soil in portions of a bench was more compact or wetter than the rest, or the soil had large clods, they would almost certainly reach a minimum of 140°F. It is obvious that the margin of safety decreases with the treatment temperature. This situation is not different from other agricultural practices today that operate on closer tolerances and with greater precision than in the past. Abundant experience shows that after 212°F steaming, unheated areas may remain as foci of contamination if the work is improperly done. The difference between 212°F and 140°F treatment is, therefore, one of degree rather than type. Aerated steam moves in the same manner and rate through the soil as does pure steam.

How is Aerated Steam Produced? The simplest way to produce aerated steam is to join together a pipe of flowing steam and one of flowing air so that the gases intermingle. If a needle valve is placed in each pipe, the total flow rate can be determined by controlling the steam flow, and it can then be adjusted to the desired temperature by manipulating the air flow.

The air is best supplied by a blower. The type of blower depends on the amount of frictional resistance in the system to the flow of air (i.e., static or back pressure). Straight blade centrifugal blowers are generally used because they are relatively inexpensive, rugged, and provide a static pressure (about 6 inches of water) sufficient for most soil steaming. Squirrel-cage blowers are not suitable because they supply only 2-3 inches static pressure. Higher pressures can be generated by centrifugal blowers with backward curved blades or by Roots's Blowers, but the cost is excessive, and the power requirement high. Piston compressors supply small volumes of air at high pressure, the reverse of needs for soil treatment. Venturis were used for a time, but are now rarely used. The size of the blower in cubic feet per minute, and the pressure it will delivery must be scaled to the job. If too small a blower is used, it will be impossible to bring the soil to temperature in 30 minutes, if too large, "blowouts" will become a problem. Table 1 will be useful in determining approximate blower size as well as boiler capacity.

Table 1. Flow rate of air and steam required to heat one cubic yard of U.C.-type soil mix to the indicated temperatures in 30 minutes at two levels of operational efficiency. Computed on the basis of soil and air temperature of 70°F, and soil moisture 15%.

		30% Efficiency		50% Efficiency	
Treatment temperature (°F)	Air-steam ratio (by weight)	Air (c.f.m.)	Steam (lb./min.)	Air (c.f.m.)	Steam (lb./min.)
212	0:1	0	7.80	0	4.68
190	0.9:1	80	6.57	48	3.94
180	1.5:1	123	6.04	74	3.62
170	2.3:1	170	5.47	102	3.28
160	3.3:1	220	4.94	132	2.96
150	4.7:1	276	4.37	166	2.62
140	6.5:1	336	3.84	202	2.30

Steam usually is injected into the air stream somewhat before it enters the treatment chamber, and the rate of steam flow is manually controlled by a needle valve. The air flow is controlled by a damper on the blower intake or a damper bypass on the blower outlet. In a typical installation the blower is connected to the treatment unit through a flexible wire-reinforced neoprene hose of about 6-inch diameter. A thermometer inserted into the tube at the point where it enters the treatment unit will indicate the temperature of the steam-air mixture. The thermometer *must be accurate in the range used.* Good quality *chemical thermometers must be used, and should be calibrated* against one of known accuracy.

The soil should reach the desired temperature in 30 minutes or less and be held at that temperature for 30 minutes. The *flow may be reduced after the desired temperature is attained,* and the steam shut off after the treatment period. The continued air flow will then rapidly cool the soil by evaporative cooling, permitting prompt use of the soil in planting. The temperature need not be brought below 90°F. An oiled fiberglass filter should be placed over the blower intake to remove dust from the air, at least during the cooling cycle, to prevent contamination of the cooled soil by dust-borne microorganisms.

Methods of Treating Soil with Aerated Steam. It is possible to treat soil with aerated steam by any of the standard methods used for soil steaming by nurserymen and florists.

Subsurface Steaming. Buried perforated pipes or tiles may be used for aerated steam, but the size of the pipes or tiles must be greater than for steam alone because the volume of gases at 140°F is 4.1 times that of steam alone, In the soil bin, mobile bin and potting bench, dump truck, and steam box types, a basal plenum should be used instead of perforated pipes to introduce the steam. This plenum should be 4-6 inches high and covered with a perforated steel plate or a strongly supported expanded metal screen on which the soil rests. The mobile bin and potting table with a basal plenum has been constructed by many growers, and an American commerical unit is also available.

Surface (Thomas) Steaming. This method is commonly used on raised benches. The aerated steam is fed tangentially into and near the bottom of a circular trap to centrifugally remove entrained water drops. On all surface types of equipment such a drier is necessary to prevent production of a wet spot below the point of injection. The dried aerated steam is then introduced under the canvas bench cover in the usual manner for the Thomas method. The cover must be held down on the bench with wood strips clamped to the sides, because of the great volume of aerated steam introduced. The method is almost worthless on benches with tight bottoms, or on ground beds with inadequate bottom drains, and should be supplanted by buried pipes under these conditions. A modification may be used on the mobile bin and potting bench by using a plenum lid on top, with the bottom plenum acting as an exhaust chamber. The outlet opening of the exhaust chamber should be the same diameter or smaller than the input opening of the injecting plenum. Commercial New Zealand and Australian units are available in which the controls are completely automated.

Vault Steaming. Flats, pots, or other containers of soil are placed in a closed chamber or vault into which straight steam is released without pressure and mingles with the air. The temperature slowly rises as the air is expelled through cracks around the door or through an open release valve. Since the vault space is occupied by the air which mingles with the introduced steam, no air need be added until the steam-air mixture attains a temperature about 20°F below the desired treatment temperature. The blower is then turned on to establish the upper treatment temperature. It is not desirable that the vault be air tight unless the spent aerated steam is to be recycled through the blower. If the aerated steam is released into the top of the vault, it must be centrifugally dried, as for surface steaming; if it is introduced at the bottom, this is unnecessary as the vault will act as the water trap.

The containers in the vault should be separated by at least 1/2 inch in each direction to facilitated steam penetration. Heating the soil in the containers is largely from diffusion of steam into the exposed soil surface. The last point to attain temperature in a pot or flat is thus in the center about 2/3 of the distance down from the top. No container to be treated in a vault should hold more than a half cubic foot of soil.

Transit-type Concrete Mixers. These units have come into general use for soil mixing in nurseries and glasshouses, and more recently this operation has been combined with soil steaming. Since the soil is constantly tumbling through steam, and since the mixer is filled with air, this equipment in effect uses aerated steam. The time of injection of straight steam determines the temperature; when the desired temperature is reached the steam flow is decreased to a level just sufficient to hold the temperature for 30 minutes. The mixer *must* be less than half full for satisfactory mixing and steaming, and the surface of the drum should be insulated with a foam plastic.

Advantages of Treating Soil with Aerated Steam. There are several advantages in using aerated steam rather than 212°F steam in treating soil, some of which will appeal to one and some to another grower.

1) There is less chance of destroying soil microorganisms antagonistic to plant pathogens when treating at 140°F than at 212°F. There is, therefore, a reduced chance of an accidentally *introduced pathogen luxuriating and causing severe disease* loss. This biological buffering effect is a reinforcement of reasonable sanitation, not a substitute for it. This protective effect does not result when essentially sterile media (sand mined from

deep deposits, perlite, vermiculite) are used. The treatment selects microorganisms, it does not create them. The microorganisms that survive the 140°F treatment are largely in genera recognized to be potential antibiotic producers. The spores of these antagonistic bacteria and fungi are stimulated by 140°F treatment to greater germination and growth, increasing their relative proportion in the active soil population. Most weed seeds are also killed if the soil is kept moist for three days prior to treatment.

2) The toxicity of soil to plants that is often induced by steaming to 212°F does not occur when treated at 140-160°F. In such toxic soils seedlings may be killed or severely injured, and yield of mature plants may be reduced. The usual experience of growers is that an increase in size and vigor of plants results when soil treatment temperatures are lowered. For example, water-soluble manganese is released from the soil colloids by excessive heating. Some soil fumigants also leave a toxic residue (e.g., methyl bromide is injurious to carnation and snapdragon).

3) Because the temperature is raised only about half as high at 140°F as at 212°F, there is a substantial reduction in the quantity of steam used. This means lowered cost, greater treatment capacity from a given boiler, or both. The saving in fuel will largely offset the expense of supplying the necessary air for treatment.

4) The soil cools more rapidly to temperatures suitable for handling or planting when treated at 140°F than at 212°F. By continuing the air flow after treatment the temperature may be lowered even more quickly by evaporative cooling.

5) Workmen are not burned in handling aerated steam at 140°F, as they may be at 212°F, and experience less discomfort. Several growers have indicated that they would continue the use of aerated steam for this reason, even if there were no other advantages.

6) Plastic pots and small divided inserts for flats can be safely treated at 140°F without deformation, and some withstand 160°F. This permits treatment of the soil in the containers, and reduces handling following treatment with its attendant opportunity for contamination.

7) The "weed molds" (*Peziza ostracoderma*, *Trichoderma viride*, *Pyronema confluens*), prevalent on soil treated at 212°F/30 minutes, are largely suppressed on soil treated at 140°F by the surviving resident antagonistic microflora.

Epilogue. As with any new method not fully understood, some misconceptions have arisen about the use of aerated steam for soil treatment. It is thought to be expensive, complicated, and difficult to use. However, almost any treatment equipment used for 212°F steam can be used for aerated steam. The only additional equipment needed is a blower, and the added expense is minimal. Operation is similar to, and no more complex than that for straight steam. Grower experience in many different areas in the last 14 years has been in accord with these facts.

Some have mistakenly thought that, because of remaining soil antagonists after aerated steam treatment, sloppy sanitary operations can be allowed. This treatment is supplemental to good grower practices, not in place of them.

Aerated steam is today a practice of demonstrated feasibility, economic desirability, and beneficial though still largely unexplored biological potential. Since the ultimate test of any soil treatment is the subsequent contamination by pathogens, the use of aerated steam treatment is here to stay.

REFERENCES

1. Aldrich, R.A., M.E. Schroeder, R.A. Keppeler, and G.H. Diener. 1975. Heating soils, soil mixes and soil substitutes with saturated air. *Penn. Agric. Exp. Sta. Bull.* 800: 1-36
2. Baker, K.F. 1969. Aerated-steam treatment of seed for disease control. *Hort. Res.* 9: 59-73.
3. Baker, K.F. 1971. Soil treatment with steam or chemicals. pp. 72-93. *In* Geraniums (J.W. Mastalerz, ed.). Penn. Flower Growers Manual. 2nd ed. 350 pp.
4. Baker, K.F., and C.N. Roistacher. 1957. Heat treatment of soil. Principles of heat treatment of soil. Equipment for heat treatment of soil. Calif. Agric. Exp. Sta. Manual 23: 123-196, 290-293, 298-301.
5. Johnson, D., and K. Aas. 1960. Investigations of the technique of soil steaming. *Acta Agric. Scand. Suppl.* 9: 1-69.
6. Morris, L.G. 1954. The steam sterilizing of soil. Natl. Inst. Agric. Eng., Silsoe, England, Repts. 14: 1-32, and 24: 1-22.

QUESTION BOX

WILLIAM SNYDER: Now, do we have some questions for our panel?

VOICE: In the case of certain of these biological control tools, particularly the behavior-modifying chemicals and the insect growth regulators, are there any side effects on the environment?

CARLTON KOEHLER: We don't recognize many, but I should point out that in the case of some of the behavior-modifying chemicals, in the case of pheromones, for example, that since these are used to either control, repel, attract, or mitigate they are considered pesticides by the EPA and, therefore, must be evaluated as any pesticide. So there is going to be a long delay in these materials appearing commercially because they have to undergo a series of tests, even though they are naturally-occurring products. But I know of no particular environmental impact that any of these classes of compounds is going to have.

VOICE: When you are using insects to control other insects, once the beneficial insect has consumed the pest insect, do not the beneficial insects move on?

CARLTON KOEHLER: The answer is yes. They have got to have hosts on which to feed. So you always must have a residue of insects in order to keep these things going.

PAUL MOORE: Dr. Baker, you didn't mention the length of time for the aerated steam treatment. Are we to infer that a 30 or 40 minute treatment at 140°F is correct?

KENNETH BAKER: Yes, I am glad you raised that point. In order to simplify the situation we have tried to standardize on a 30 minute time interval, and use the temperature as the variable. If everybody uses a 30 minute interval, at a certain temperature you know that you will achieve a certain result. If you suggest 135°F for 35 minutes, for example, you have a chaotic mess. We are trying to eliminate the time variable by standardizing it.

VOICE: What are the common names of the fungicides mentioned?

ROBERT RAABE: Benomyl is sold at the present time principally as Benlate. Ethazol is sold primarily by the name Terrazole if it is manufactured by Olin Company; if it is produced by Mallinckrodt it is Truban or Koban. Koban is used principally on turf; Truban is registered for use on ornamentals. Truban can come either as a wettable powder or as an emulsifiable liquid, either of which does an excellent job. Diazoben is sold principally as Dexon. Thiophanate methyl is marketed under the name of Cercoban M or Topsin M or Xyban, depending upon who makes it.

VOICE: Can you use Ban-Rot at 6-month intervals?

ROBERT RAABE: Ban-Rot is a mixture of Truban and thiphanate methyl. It is a very good mixture because it does cover a range of different fungi which are all important. The length of time that they will last in the soil will depend upon how you are using your soil. If you have soil in containers and you have a disease problem, we find you should use these materials at approximately one-month intervals, although you may skip and use them at two-month intervals. It depends upon how much disease control you get when you use it and how many disease-producing organisms you have present. You just sort of have to feel your way along.

VOICE: Can you treat carnation cuttings to control *Botrytis* with a dust material as readily as with a solution?

ROBERT RAABE: I don't know. We haven't tried it. Maybe we should try. We have used dusts in other areas and generally we find we do not get as good coverage with a dust as we do with the dip, therefore we do run into some problems. We haven't tried it on carnations. I think it might be a good idea to try.

PHILIP BARKER: I would like to ask Dr. Baker a question. In the absence of a boiler, what type of portable steam generator do you recommend?

KENNETH BAKER: One should explore the availability of stand-by boilers that are operated in most cities that have any sort of manufacturing or commercial operations. You can have them brought in to supply steam at so much an hour or a day. The Clayton Boiler Company has truck-mounted boilers in cities that have need for them. One of the common misconceptions is that steaming is an expensive operation; but if you work it out on a pro rata basis it actually is no more expensive in the long run than using chemical fumigation, or any other form of soil treatment. Think of it on a 10 year basis on the cost of the boiler. Even if you borrow the money, it still pays off. But if there is a possibility of using one of these rental services, I would do it. You can find these rental boiler companies listed in the yellow pages of the phone book. These are commercially available in case a boiler breaks down and will provide boiler service while their own equipment is being repaired.

Using the right size boiler to do the job is a matter of sizing it to the number of cubic yards of soil to be treated at one time.

VOICE: Dr. Baker, could you explain further about filtering the air into the boiler?

KENNETH BAKER: You do not inject air into the boiler; you inject the steam into the air flow from the blower. The filter simply goes on over the input of the blower. The fiberglass that is sprayed with oil — just as you do with the air filter in your car — is to keep out dust.

BRUCE BRIGGS: Where are we in terms of biological control of plant pathogens?

KENNETH BAKER: Essentially it comes down to two things that are being done. One is manipulation of the soil environment to make it more favorable for antagonistic organisms already present. An example of this is provided in the state of

Washington in control of fusarium foot rot of wheat. They know that if their moisture level declines appreciably — it doesn't have to go down very far — the antagonistic bacteria present in the soil become inactive — go into a spore stage. These bacteria, while active, suppress *Fusarium*. The problem thus becomes one of keeping wheat soils moist longer. They are doing this in three ways: (a) they plant the wheat late so that the plants don't get so big; (b) they do not use any more fertilizer than necessary to get the yield they wish. The soil stays moist longer, the bacteria are active longer, and the fusarium is suppressed. (c) different varieties vary greatly in the amount of water they use. The varieties now used have a better water economy; the soil stays moist longer, the bacteria are effective longer, and the disease is less troublesome. That is environmental manipulation.

The other type of control, and I think the one Bruce was alluding to, is to treat soil or add antagonistic microorganisms to it in order to accomplish biological control. In the nursery and florist industry this is particularly promising, because you generally are adding single organisms. When you do this it is almost necessary to get rid of organisms already present. It really doesn't matter whether you treat soils with methyl bromide, chloropicrin, or steam. You reduce the population that is there, then add an antagonist to it. This works very effectively under these conditions. But it does not seem to work under field conditions where the soil is not treated to get rid of the existing microorganisms. Single antagonists work well in treated soil, but have not been very practical in field use.

BILL SNYDER: Thank you very much, Ken. I would like to thank the three speakers from Berkeley, Dr. Raabe, Dr. Koehler, and Dr. Baker for coming down here this evening and discussing these three very interesting topics with us.