Thermal weed management for crop production

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1. Introduction

Thermal weed management, e.g., flame and steam weeding, is a valuable physical weeding technique that can achieve results that are not possible with other physical weeding technologies such as cultivators. However, thermal weeding is generally more expensive than alternatives due to higher capital and running costs plus slower working rates. It is therefore mostly reserved for those situations where other techniques do not work at all or do not work very well.

While many possible thermal techniques have been tested, (e.g., microwaves, UV light, lasers, liquid nitrogen, electricity (mini-lighting bolts) focused sunlight, etc.) only flame and steam have met the key agricultural criteria of efficacy, safety, mechanical simplicity, robustness and reasonable cost. Of these two steam weeders are in their infancy and their extra mechanical complexity and therefore price, plus considerable water consumption, means that they are a less attractive option unless one or more of steam's unique attributes are essential, i.e., near-zero fire risk, much lower temperature and ability to use liquid fuels such as diesel and vegetable oil. As steam weeders are not yet widely available this article will focus on flame weeding, although the theoretical background applies equally to both.

This article is not a simple 'how-to' or 'recipe' for thermal weeding. There are too many variables to be able to provide such advice, rather it provides more fundamental information to allow you to understand the principles of thermal weed management so that you can adapt, rather than simply adopt them to your farming and growing situation.

2. How heat kills plants

To get the most out of thermal weeding, and to avoid costly mistakes, it is essential to understand how heat kills plants as well as the basic physics of heat.

For both steam and flame weeders heat is transferred from the weeder to the plant by 'forced convection' i.e., it is literally blown at the weeds. This is a very fast process taking a few seconds or less to move the heat several feet. However, once the heat reaches a plant's surface, it can only move through the plant's tissues by conduction. This is a tortuously slow process with the heat moving only a fraction of an inch over tens of seconds. This is a problem, because for heat to kill a plant it has to kill all its aerial meristems (buds), which reside in the leaf axils in dicots and in the center of the stem in monocots.

There is a widely known test to give an instant determination if a flame weeder has 'done the job' which is to squeeze a leaf between finger and thumb, and if the leaf takes up a fingerprint the flamer has achieved the result. However, this test is inaccurate as there may have been enough heat to kill the leaf, but not enough to kill the buds at the base of the leaves, in which case the weed will only be defoliated, not killed, and will therefore regrow. If setting the weeds back is all that is required, then this is fine, but if complete weed kill was desired, then this is clearly not good enough. Therefore, understanding the difference between destroying a plant's leaves to defoliate it and killing its buds, thereby killing the whole plant, is absolutely fundamental to understanding thermal weeding.

If the heat cannot get at the weeds or the crops buds, then it can't kill the plant. For example, the monocots, e.g., grass, cereals, maize / corn and alliums, which have their apical bud situated at the center of their leaf bases, often just below ground, are hard to kill as the bud is well protected. In comparison dicots, such as lambsquarters (*Chenopodium album*) and beans, mostly have their apical meristem at the top of the plant and their lateral buds at the base of the leaves in the open air, so it is much easier to get heat into their buds. The exceptions to this are where dicots have a growth form closer to the monocots, for example, where they have a highly shortened stem, such as carrots, and shepherds purse (*Capsella bursa-pastoris*) i.e., they have a rosette growth form. Such growth forms protect the buds, making such plants much harder to kill.

The second problem caused by the slow transfer of heat by conduction within plants is that as plants grow, there is an exponentially greater amount of plant tissue to heat to be able to get sufficient heat into the plant to kill the buds. Plants therefore generally become very rapidly resistant to thermal techniques as they grow unless exponentially larger amounts of heat are applied. Weeds should therefore always be treated as small as possible, i.e., at the cotyledon stage, with many becoming partially resistant to normal heat doses around six true leaves.

This information allows you to make a estimation if a thermal weeder will be able to kill or not kill weeds and crop plants, therefore making better use of the technique as well as being able to use more advanced techniques such as selective thermal weeding, discussed below.

2.1. Infrared weeders

There is a second type of flame weeder that transfers heat by infrared light (radiation) generated by burning gas in ceramic elements, however, these are less common than open flame weeders. The problem with transferring heat by infrared light, is that the heat can only be absorbed by the parts of the plants that the infrared light can 'shine' onto, just as if it were visible light. If one part of the plant, e.g., a leaf, casts a shadow, i.e., 'shades', another part, e.g., a bud, then the shaded part wont be heated and will therefore be unaffected. Once the heat reaches the plant surface it then moves by conduction through the plant tissues the same as for flames or steam. This shading effect means that in general, infrared weeders, have lower flexibility than open flame weeders. The ceramic elements are also fragile and expensive making them less suited for agricultural use.

2.2. 'Thermal dose'

The concept of 'thermal dose' i.e., how much energy is applied using a thermal weeder is reasonably analogous to herbicides, but slightly more complex and is unfortunately an area of misunderstanding. The key concepts to understand are energy, power and temperature.

To heat something up, i.e., to raise its temperature, requires energy. The amount of energy required to raise the temperature by a given amount, e.g., from 20° to 80° C depends on both the specific heat capacity of the material and the weight (mass) of the material to be heated but nothing else. Therefore, for a given amount (weight) of weeds / plants at ambient temperature there is an exact amount of energy required to heat them up to the point at which they will die. This means for any given area of field covered in weeds of a given size (weight) the amount of energy needed to kill them, and therefore the amount of fuel required, is completely fixed. Therefore, having a thermal weeder with a higher power output (bigger engine) simply means that the weeding job can be done faster, as more energy is put out per unit time (just as a bigger tractor can do the same tillage job faster than a smaller tractor), i.e., having a more powerful thermal weeder does not mean that it will do a 'better job', it only determines how long the job will take. The corollary of this is that, as speed at which a thermal weeder is used at changes, the energy it puts out per area of land changes by the same amount, so to vary the thermal dose you simply have to drive the weeder faster or slower.

There is one assumption in the above statements: that the higher and lower powered weeders are equally efficient (effective) at getting heat into weeds. In tractor terminology they have the same fuel efficiency. However, a flame weeder that is twice as powerful but with lower efficiency than an alternative machine will not be twice as fast as the lower powered weeder. Indeed a very powerful but very inefficient machine may well be slower than a lower powered but highly efficient machine that gets most of its heat into the weeds.

2.2.1. On-farm dose-response trials

While the above information allows you to make an estimation if thermal weeding will, or will not, be able to kill any given weed or crop species at a particular size it is just an estimation, not a prediction. Only conducting a 'real-world' test will confirm if the estimation is correct or not. The dose-response trial is the best method of confirming such estimations.

Trying to work out what the optimum speed / thermal dose for any given crop and weeds, depends on multiple factors, such as the effectiveness of the thermal weeder and the species, population, size and shape of the weeds and the crop. It is therefore impossible to work out theoretically and therefore has to be done by trial and error, i.e., experimentally. The simplest way to determine what the optimum thermal dose, i.e., the best driving speed, for your own flame weeder on your farm on your weeds and crops is to simply test your weeder at a range of speeds, e.g., 1, 2, 3, 4 and 5 mph, each over a 20 to 50 yard length of ground covered with your typical weed weeds and see at what point the treatment no longer kills the weeds or starts harming the crop. Using this technique you can build up experience of what your weeder will achieve on your farm, on the kinds of weeds you have in your crops, just as you build up experience of what kind of yield you would expect from a particular cultivar / variety which will differ from other farmers and growers.

3. The main thermal weeding techniques

There are two main uses for thermal weeders: the stale seedbed and intrarow selective flaming of established crops. The former is the main technique in Europe while intrarow flaming has mostly been practiced in North America. There is also a novel third approach - broad acre selective thermal weeding where the aerial parts of the crop are destroyed along with the weeds but the crop regrows while the weeds are killed.

3.1. Stale seedbeds

The stale seedbed technique is mostly reserved for high value, direct sown crops which are poor weed competitors such as carrots and onions. It can be used on other direct-sown crops, e.g., cereals, but it is rarely cost-effective in such situations.

The term 'stale seedbed' is used to describe a number of different techniques, such as bastard fallows and false seedbeds, however, it best describes the use of thermal weeders for pre-crop emergence weed control. The stale seedbed is based on two principles:

1. tillage is the most effective means of encouraging weed seeds to germinate;
2. weed seeds germinate and emerge very quickly after tillage.

i.e., you get a big and rapid flush of weeds after tilling the soil.

The stale seedbed takes advantage of these rules by delaying planting for several days or weeks after the final tillage operation (Figure 1). This allows the weeds to start germinating ahead of the crop. After a suitable delay the crop seeds are sown into the emerging weeds, and then just before the crop emerges a thermal weeder is used to kill the weeds. The crop then emerges into weed-free soil and because there has been no further soil disturbance (tillage) to encourage more weed seeds to germinate few weeds should subsequently emerge in the crop. The name 'stale seedbed' refers to the fact that the crop is sown into a seedbed than has not been freshly created but that has been around for some time i.e., it has therefore become 'stale' as in lost its 'freshness.'

Timing is critical! If thermal weeding is undertaken too late, i.e., after the crop has emerged the crop will be killed (with the exception of some monocot crops, see later). If weeding is undertaken too soon, not all of the weeds will be killed, and, as they have a head start over the crop, will be much more troublesome than weeds that emerge with or after the crop. Therefore, correct timing is everything as failure to get the timing right can result in complete crop loss or weeds taking over.

The most common technique to predict crop emergence is to accelerate the emergence of small sections of crop by placing frost protection covers, or sheets of glass raised off the soil by about half an inch, in several locations across the crop. When the crop appears under the covers or glass then thermal weeding must be undertaken immediately, as the next day will almost certainly be too late.

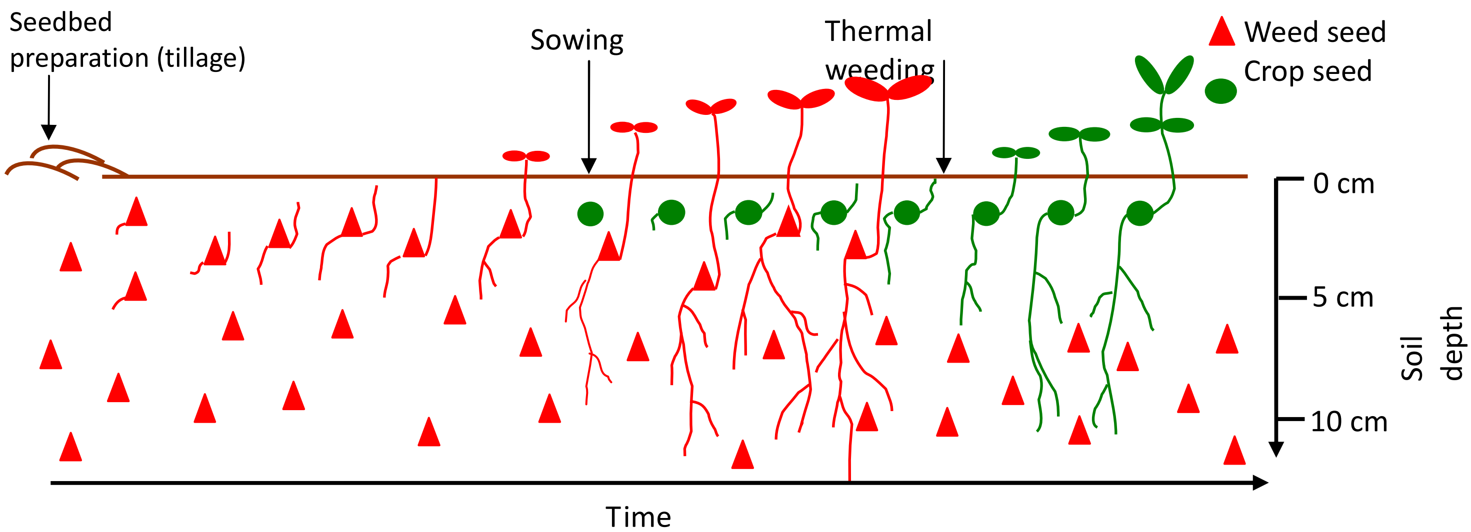

Figure 1. Illustrative scheme of a stale seedbed: Final seedbed is prepared, weed seeds in top two inches (5 cm) of soil germinate, crop is sown into the now 'stale' seedbed, weed seedlings emerge, immediately prior to crop emergence weed seedlings are killed by thermal weeder, crop emerges from weed free soil.

The time delay between tillage and planting depends on how fast the weeds emerge and how fast the crop emerges. These times will in turn vary with crop and weed species and the time of year, with emergence being slower in cooler and dryer conditions than warmer and wetter ones. It is therefore essential to determine these times for your own farm's, crops and weeds rather than rely on other farmers times or those from research. To work out the post-tillage planting delay subtract the expected time to from sowing to emergence for the crop, from the time it takes the weeds to emerge after tillage (but not grow too large). Clearly this is a very variable figure! Being cautious and delaying sowing by a few days to give the weeds more chance to emerge can be beneficial as long as such delays are not problematic themselves, e.g., the weeds get too big.

Where there is the potential for considerable time delay (weeks even months) between tillage and sowing, multiple thermal treatments could be used to kill successive flushes of weeds. However, such an approach may not be the most effective or economic. Instead several false seedbeds (using tillage to kill the weeds) could prove a better, or at least cheaper option. Again, which strategy is best will vary considerably among farms and crops so it is best to trial different techniques on your own farm. See http://www.merfield.com/research/organic-weed-management-a-practical-guide.pdf and http://www.physicalweeding.com/information/index.html#falsestaleseedbeds for more information on the false and also stale seedbed techniques.

3.2. Intrarow thermal weeding

In contrast to the stale seedbed technique where the crop has not emerged at the point of flaming, in intrarow thermal weeding the crop is normally well established at the time of thermal treatment.

Intrarow thermal weeding works by having one or more pairs of torches positioned either side of the crop row, with the flames aimed at the base of the crop stem, i.e., the intrarow area (Figure 2 and Figure 6). The technique relies on the crop having considerably greater 'resistance' to the thermal treatment than the weeds thereby allowing the crop to survive while the weeds are killed or at least significantly retarded in their growth.

The theory behind this is outlined in Section 2 'How heat kills plants.' An additional aspect of plant morphology that is key to the success of this technique is the how heat resistant the crops' stems are, because the heat is aimed at the base of the crop stem. To make an extreme example, a tree with thick bark is clearly going to be much more resistant to having a flame pass over its trunk than a thin lambsquarter seedling. Therefore annual crops, such as maize, cabbage, cotton etc., at larger growth stages when they have thick tough stems and perennial crops such as tree fruits, e.g., apples and cane fruit, e.g., raspberries, are more resistant to thermal treatment than small weeds with thin stems. A critical addition to the information in Section 2 is that the cambium layer, which lies under the 'bark' of the plants is also a meristem. Unlike buds which are point-like, the cambium is cylinder shaped as it is wrapped around the stem. It generates the phloem and xylem vascular tissues rather than leaves and shoots. Killing the cambium and/ or the phloem (which is also living tissue unlike the 'dead' xylem) will kill the plant. This is the same effect as ring-barking a tree, i.e., it deprives the roots of energy (from photosynthesis) so they die and hence the whole plant dies.

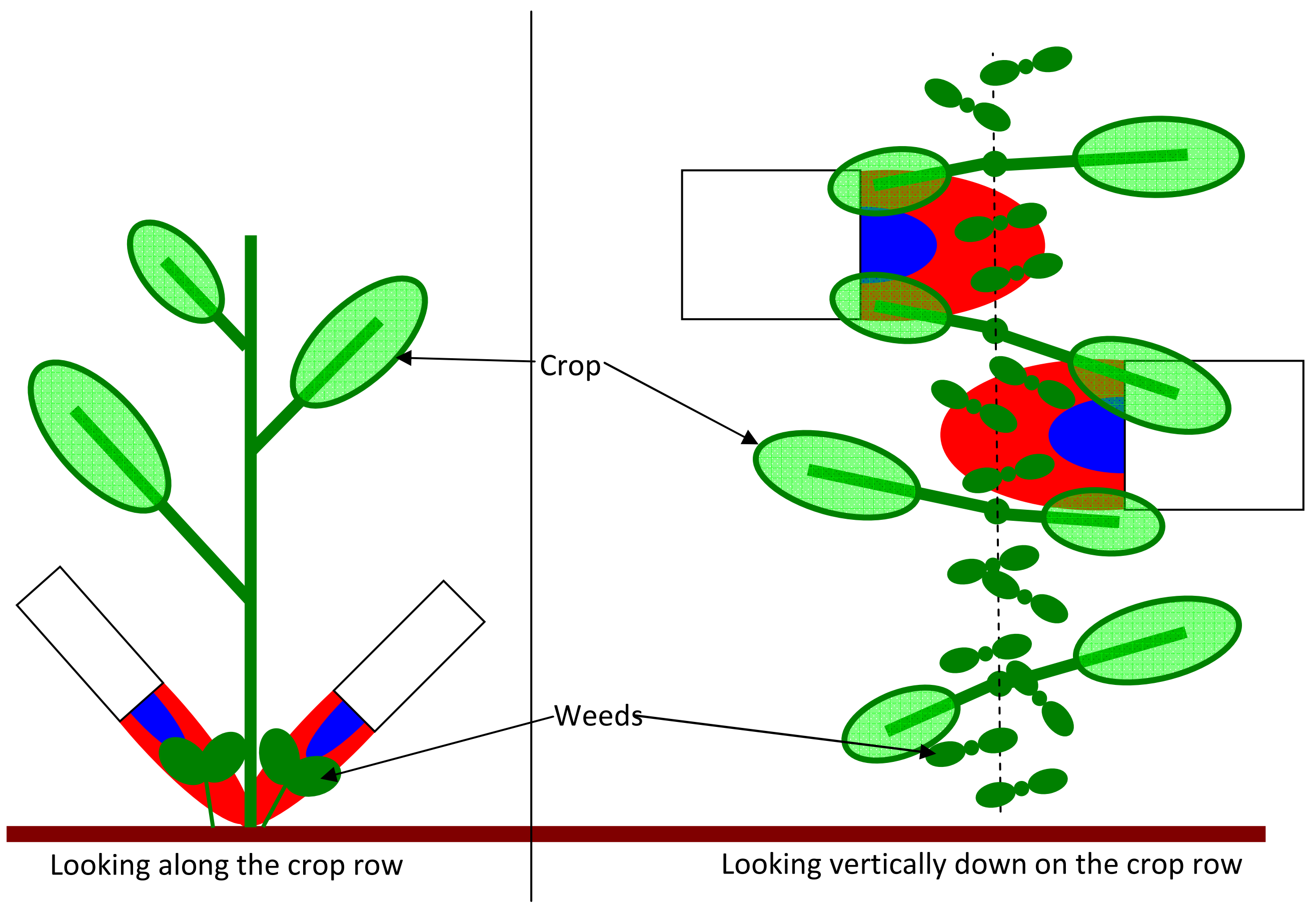

Figure 2. Diagram of intrarow flame weeding showing flames angled towards the base of the crop stem, and typically staggered along the crop row so the flames do not 'interfere' with each other.

Ensuring that the crop can tolerate the heat dose while the weeds are sufficiently susceptible is clearly critical to the success of this technique. If more heat is applied than the crop can tolerate it will die, or at least, be significantly set back. To little heat and the weeds will not be killed or sufficiently harmed, so little or nothing will be gained from the time and money spent on the flame weeding. However, providing off-the-shelf recommended doses (i.e., driving speed) is, once again, not possible as different flame weeders can have quite different results for the same heat dose. Individual crop species also differ in their levels of tolerance and their tolerance will change at different growth stages. The different weed species and sizes will also range from highly susceptible to highly resistant. What is recommended is for farmers work out for themselves what doses of heat their crops can tolerate at the time that intrarow flame weeding would be beneficial, by conducting their own dose response tests on a small 'sacrificial' section of crop. See section 2.2.1 'On-farm dose-response trials' for more information. When conducting such tests for intrarow thermal weeding it may not be essential to completely kill the weeds- defoliating them may be sufficient to give the crop a competitive edge, and/or achieve other objectives e.g., reducing the amount of seed the weeds produce. Also if the 'ring-barking' effect, i.e., killing a collar of phloem and cambium, is being achieved, both for the weeds or the crop, it may take many days, even weeks for the effect to show up. Therefore, just because the weeds and/or crop do not obviously die within a day or so of treatment do not assume that they wont die in a few weeks.

It should not be assumed that thermal weeding is the only option for controlling intrarow weeds, especially in established crops. Standard weeding techniques such as cultivators fitted with tools such as ridgers, finger weeders, torsion weeders etc. may well be able to do as good, or better job, more quickly and for less cost.

3.3. Broad-acre selective thermal weeding

Broad-acre selective thermal weeding is not a technique for the faint-hearted nor should it be undertaken without on-farm validation that it will work with the crop / weed combination in question. The technique only works for crops that are highly resistant to thermal treatment due to their growth habit: either the apical bud is underground / in the center of the stalk, i.e., the monocots / grasses e.g., cereals and onions or they have their apical and lateral buds protected by a rosette growth form (dense whorl of leaves) e.g., carrots.

The technique uses a flame weeder to destroy all of the above ground foliage of both the crop and weeds. Although the crop looses its leaves, its protected growing points mean that as long as it has sufficient underground reserves it can regrow. If the weeds have an upright habit with poorly protected growing points e.g., lambsquarters and they are not too big they will be killed.

There are a large number of caveats associated with the technique. Most crops vary significantly in their tolerance / susceptibility as they grow. For example, carrots are highly susceptible until they have formed their rosette, before this time 100% carrot mortality would be expected. Defoliating the crop may well have negative effects on future growth and yield, to the point that yield is decimated. The size of yield reduction nearly always varies with crop growth stage with a rough rule of thumb being the later the thermal treatment the greater the final crop damage / yield loss, although there are exceptions to this rule where earlier treatment results in bigger yield losses. Further, negative effects on yield, especially for grain and seed crops may not be easily visible, i.e., just because the crop appears to recover OK does not mean yield will not be significantly decreased.

In summary broad-acre selective thermal weeding is NOT suitable for routine use until sufficient on-farm research has been undertaken to determine the impacts on different crops under a range of conditions. However, in situations where a crop would otherwise be lost to weeds and / or there is no alternative economic means of removing the weeds then the technique may be a 'get-out-of-jail-card' as some crop is better than no crop. Again, due the large number of variables, i.e., crop and weeds, growth stage, time of year, type of thermal weeder, it is not possible to give guidance for the thermal dose required - this can only be established by testing on a sacrificial area of the crop and weeds in question. See section 2.2.1 On-farm dose-response trials for more information.

To repeat: do not 'bet the farm' on this technique until you are very experienced with its effects or you may well loose the farm.

4. Machinery

4.1. Flame weeders

The machinery required for thermal weeding does not have to be expensive or complex, although the most efficient designs generally are. Simple hand-held torches (Figure 3) connected to small, e.g., 50 lb (25 kg) LPG bottles, typically used by builders and highway maintenance available from local hardware stores, are highly effective for small areas, when correctly used. Their simplicity also makes them flexible so they can be used for both stale seedbeds as well as intrarow selective flame weeding.

Figure 3. Typical hand-held builders torch (left) twin burner setup (right).

Figure 4. Pedestrian propelled bed flame weeder (photo courtesy of Dr Eric Gallandt).

The first size up from hand held flame weeders are pedestrian propelled machines (Figure 4) which often make the flame weeding job much easier and also effective due to controlled burner height.

For larger scale operations that use tractors the same kind of torch head as used on a hand-held lance, can be connected in a row to treat whole beds or just the crop rows (Figure 5). Such set-ups are relatively inexpensive, although they will require larger capacity pressure regulators and much bigger fuel bottles to ensure sufficient gas supply. However, such 'open' flame weeders, i.e., without a protected shield / hood are much less effective than hooded machines so they are only really suitable for treating small areas on an occasional basis (see section 4.1.1, Wind resistance). The same approach of using many individual torches can be used to create intrarow flame weeders (Figure 6)

Figure 5. Simple un-hooded tractor mounted flame weeder comprised of multiple torch heads to treat the whole bed (left) or to just treat the crop rows (right).

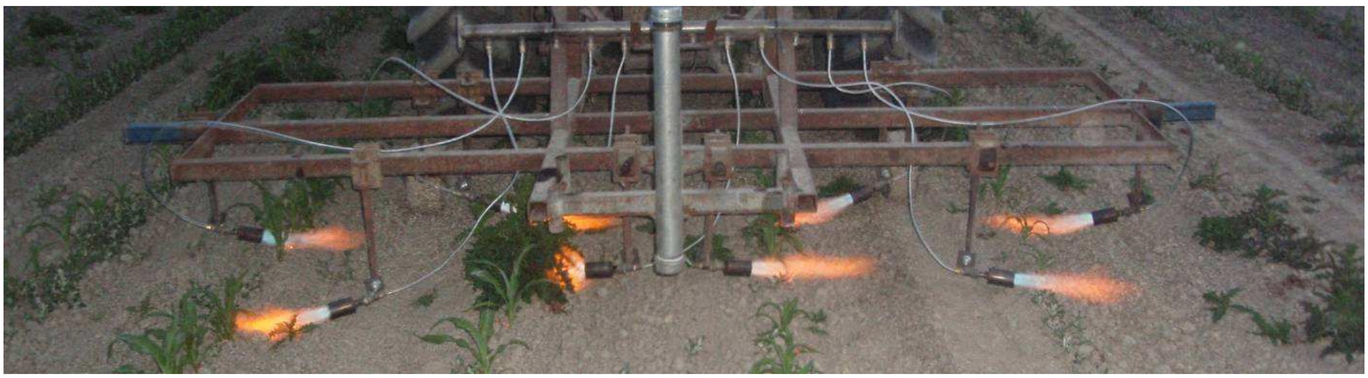

Figure 6. Simple intrarow weeder using off-the-shelf torch heads.

Where larger areas of crop need to be treated as part of the false seedbed then a 'hooded' flamer (Figure 7) should be used as this will significantly improve the efficiency of the machine and allow its use in windy conditions .

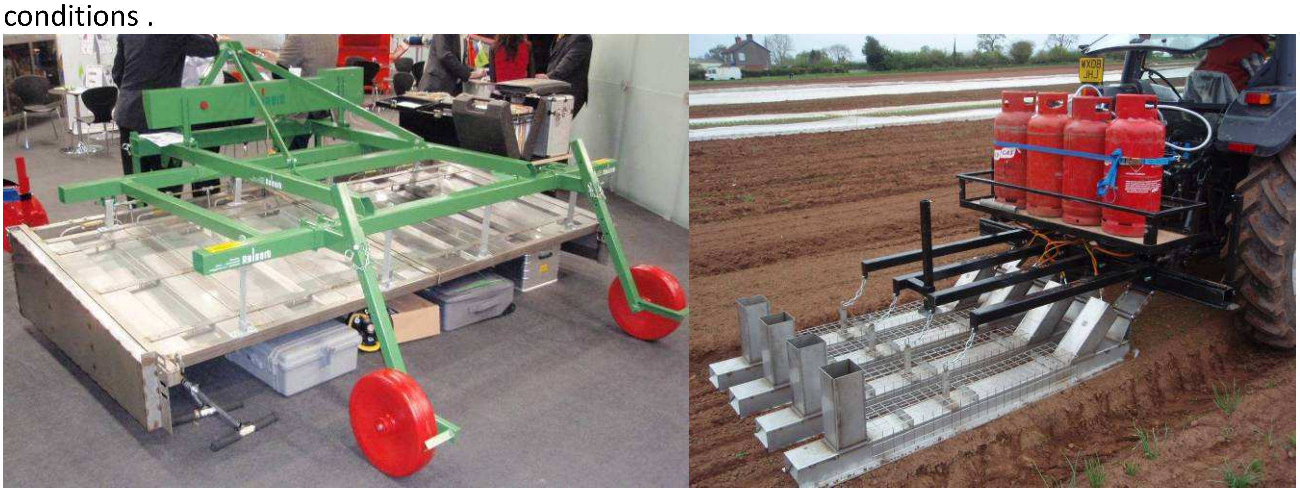

Figure 7. Hooded whole-bed flame weeder design (left), intrarow design (right).

While such machines often cost considerably more than un-hooded flamers, their much better performance and ease of use (e.g., no problems with flames blowing out) will pay off in the long term. There are a wide variety of different hood designs, in terms of their height, length, where the flames are introduced, (in front, through the top of the hood), and how exhaust gases are expelled. These different designs vary considerably in how effective they are at transferring the flames heat into the weeds vs. how much is lost as unused energy as well as how well the machines perform in adverse conditions such as wind. Key parameters are that the hood should be as long as practical to maximise the length of time plants are exposed to the heat. The hood should be as low to the ground as practical (with sufficient space to allow the hot air through and not to hit the soil) to keep the hot air close to the weeds. A simple test as to any particular machines effectiveness is to measure the amount of heat, e.g., by measuring temperature, coming out the end of the machine. The exhaust temperature of an efficient flame weeder design should be less than 300°F (150°C) when used at their optimum speed for killing weeds (travelling faster will reduce temperature but not kill weeds, travelling slower can't kill more than 100% of the weeds but will raise the exhaust temperature higher than is required, i.e., will waste heat).

4.1.1. Wind resistance

The issue of wind resistance, i.e., the flamer continuing to effectively operate in windy conditions, should not be underestimated. Flame weeding in the false seedbed technique is highly time critical - often to less than 24 hours, so not being able to effectively flame because wind is blowing the heat out of the hood, or worse blowing flames out, on the one day you have to flame weed could be very expensive due to crop loss and/or hand weeding costs. Many older open hood designs are highly susceptible to wind, especially from behind. The best designs can operate in wind speeds of 30 mph without reductions in their performance.

4.1.2. Fuel supply

Flame weeders typically use Liquefied Petroleum Gas (LPG) as their fuel, which is a mixture of propane and butane, or they use pure propane. There are two methods for 'drawing-off' the fuel from the fuel bottles / tank called 'gas-phase' and 'liquid-phase' take-off. Unfortunately the word gas has two meanings in this context - it is used to describe both the fuel (LP gas and propane) and the 'phase state' of the fuel, i.e., whether it is in a solid, liquid or gas phase. For clarity, in this section 'fuel' refers to LPG and pure propane while gas refers to the phase state of the fuel.

As the name indicates LPG is in a liquid phase state within the bottles, as is pure propane. In gas-phase take-off the fuel leaves the bottle as a gas. To become a gas from the liquid in the bottles it has to evaporate (boil) which requires energy in the form of heat, i.e., it is the same process as getting steam off water - heat (energy) has to be put into the water to make it boil (evaporate). This energy is called the latent heat of evaporation. Unlike water where heat has to be applied to make it boil at atmospheric pressure and room temperature, LPG and propane 'boil' at room temperature and atmospheric pressure. However, the heat needed to evaporate the fuel to the gas phase cools the bottles. If the rate of gas take off is sufficiently fast the bottles will cool so much water-ice will form on the outside of bottle to the level of the liquid fuel within, even in hot weather conditions. This is a particular problem for LPG because butane boils (at atmospheric pressure) just below the melting point of water at 28°F (-2°C) while propane boils at -44°F (-42°C). This means that the propane will evaporate faster from cold bottles than butane resulting in the proportion of butane increasing in the bottles. As the butane will stop evaporating at all when water-ice forms on the bottles and will evaporate only slowly as the bottle temperature reduces towards 28°F it simply can not evaporate fast enough to power even a single torch, let alone a large machine with many torches. This results in it being impossible to empty the bottles by running the flamer, so on each refill the amount of butane increases to the point that the bottles are full of un-useable butane and have to be purged by an approved gas supplier. Pure propane is therefore recommended as a fuel as it will evaporate when the bottles are much colder and there is no problem of fuel separation.

Even where pure propane is used a large volume of fuel, e.g., multiple bottles, or one large (e.g., one ton) fuel tank are required for tractor mounted flame weeders to ensure sufficient supply of gas-phase fuel at the required pressure on a continual basis. LPG requires even larger fuel supply. A suggestion ratio is an absolute minimum of 300 lb of pure propane fuel per 100 kw with 400 lb being preferable and 500 lb where LPG is used.

The alternative solution to this situation is to use 'liquid-phase' take-off, whereby the fuel is removed from the tank as a liquid and is vaporised either in the torch or in a pre-heating system, typically using heat from the flames. While this sounds a simple solution, handling liquid phase fuel is much more difficult than gas phase: more sophisticated pressure regulators and special torches are required, pre-heating must be carefully regulated to prevent overheating or under-heating and correct filling, purging, cleaning and general management of the fuel tanks is essential. Therefore, in many cases it is not a simple solution after all and the best approach is simply to have a sufficiently large amount of fuel to be able to cope with the gas-phase draw off rate.

4.2. Steam weeders

Steam weeders suitable for agricultural use are not yet commonly available. NB see the safety section below - do not attempt to build a pressurised steam system - they are highly dangerous.

5. Safety

Thermal weeding is an inherently dangerous process due to the large amount of heat produced which has the potential to seriously burn people and other things e.g., dogs. Ensure that bystanders, pets, stock etc., are kept well away from operating thermal weeders.

Flame weeders are also an obviously high fire risk so they should not be operated near combustible material, e.g., dry grass or shrubby field margins, organic (biological) mulch materials, e.g., straw, peat, compost, bark etc., plastics, e.g., sheet mulches or irrigation pipes, especially drip tapes, or when fire bans are in place. High capacity fire extinguishers should always be carried. Note: permits may be required for flame weeding operations and local authorities should be consulted for permits.

5.1. Flame weeding in confined spaces

Flame weeding in confined spaces, e.g., polytunnels and glasshouses poses a risk of asphyxiation due to the build-up of carbon dioxide and / or carbon monoxide poisoning.

As a comparison, an average person 'burns' fuel at a rate of about 0.2 kw / 200 watts (the same as a bright incandescent light bulb). A typical hand-held flame torch is around 15 to 25 kw, so one torch consumes as much oxygen and puts out as much CO_2 as one hundred people. A hundred people in a small tunnel with the doors shut would get pretty stuffy pretty quickly! Therefore, there is a considerable risk when using flame weeders in confined spaces of using up so much oxygen that the operator looses consciousness (faints / blacks out) or is killed from asphyxiation.

Carbon monoxide is produced when there is incomplete combustion - a common occurrence for flame weeders. Carbon monoxide is highly toxic and can not be smelt, tasted or seen and it can render a person unconscious without them realising and will kill at slightly higher amounts.

It is therefore essential when using flame weeders in a confined space, such as glasshouses, that all doors, and other ventilation mechanisms are fully opened and that there is a safety person outside the confined area tasked with continually monitoring the operator(s) inside. All thermal weeders used in such situations should have a 'dead mans handle' such that the weeder immediately turns off should the operator loose their grip on the control.

5.2. Steam

Pressurised steam also know as ‘superheated steam’ is exceptionally dangerous as are the pressurised steam boilers required to produce it. On no account should any attempt be made to use pressurised steam or use or build a pressurised steam boiler except by properly qualified people.

6. Conclusions

Flame weeding can be a valuable addition to the toolkit for managing weeds on organic farms. Use is generally crop-specific, with broadcast flaming widely used for broadleaf weed problems in slowly emerging, poorly competitive vegetable crops including carrot and beet. Less commonly, post-emergence directed flaming is used in relatively heat-tolerant crops including onion and maize.

The foremost advantage of flame weeding is the ability to kill small weed seedlings without disturbing the soil surface, thus avoiding the stimulation of a subsequent “flush” of weeds that would occur with a cultivator. Another advantage is that equipment is available for virtually any scale of production, from hand flaming of single beds, larger tractor mounted units several meters in width.

Notable disadvantages of flaming include relatively poor control of grasses and perennial weeds, a very narrow range of sensitive growth stages in broadleaf weeds, safety concerns, and investment costs for more sophisticated equipment.

7. Further reading

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8. Image credits

All photos by and diagrams by Dr Charles Merfield except Figure 4 courtesy of Dr Eric Gallandt.