False and Stale Seedbeds: The most effective non-chemical weed management tools for cropping and pasture establishment

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Table of contents

List of figures

1. Summary

- Globally there is a growing need for non-chemical weed management tools due to multiple and increasing issues with herbicides.
- Of the many non-chemical techniques ‘false seedbeds’ stands out due to its efficacy, ease of use, reliability and low cost plus it can be used for any kind of plant establishment from pasture through arable to vegetables.
- False and stale seedbeds are based on three rules: (1) most weed seeds are dormant, (2) tillage is the most effective means of germinating weed seeds, and (3) most weeds only emerge from the top 5 cm / 2” of soil.
- Both false and stale seedbeds work by the very simple process of germinating the weeds then killing them and then growing the crop.
    - False seedbed use tillage / cultivation to kill the weeds.
    - Stale seedbeds use thermal weeders or herbicides to kill the weeds.
- For both techniques it is critical to have the weed seed bank under control.
- For false seedbeds getting the tillage correct is utterly critical and in most cases requires specialised machinery.
- Thermal weeders (for stale seedbeds) are also specialist machines and choosing the right type and design in critical.
- When false and stale seedbeds are used as key components of an integrated weed management program exceptional weed control can be achieved without the use of herbicides.

2. Introduction

This handbook explains the related techniques of false and stale seedbeds in detail, both the underpinning theory and what it takes to implement them in practice.

Globally, there is a growing need for non-chemical weed management tools due to:

- rapidly increasing herbicide resistance;
- a shrinking number of herbicides due to their withdrawal by regulators and chemical companies;
- growing consumer concern about herbicide and other pesticide residues in food and the environment;
- the growth of organic agriculture which prohibits the use of xenobiotic materials as inputs into farming systems.

Of the multitude of non-chemical weed management techniques, one stands head and shoulders above the rest in terms of its efficacy, ease of implementation, reliability and low cost: ‘false seedbeds’. This is based on decades of real-world on-farm experience, not just research, so it well and truly farm-proven, and therefore safe for all farmers and growers to use.

And, while the concepts of false and stale seedbeds are very old, probably going back millennia, the modern, scientific understanding of the weed seedbank, dormancy and germination has resulted in refinement and a significant improvement of the techniques to the point they can rival herbicides.

To illustrate the effectiveness of the techniques Figure 1 shows a crop of direct drilled (i.e., not transplanted) silver beet / Swiss chard (*Beta vulgaris* subsp. *vulgaris*) that has received no weeding since crop emergence, i.e., all the weeds were controlled without in-crop weeding of any kind.

Figure 1. Example of the efficacy of false and stale seedbeds: crop of direct drilled silver beet / Swiss chard (*Beta vulgaris* subsp. *vulgaris*) that has received no post crop emergence weeding at all.

Figure 2 shows a crop of direct sown processing carrots shortly after emergence and approx. six weeks later after interrow hoeing, but without any intrarow weeding, e.g., hand weeding.

Figure 2. Direct sown crop of processing carrots, left: shortly after emergence, right: approx. six weeks later with only interrow hoeing, no intrarow weeding at all, with a 'token' fat hen / lambsquarters (*Chenopodium album*) in the intrarow.

3. The theory of false and stale seedbeds

The terms false and stale seedbeds are often used interchangeably and internationally there is no agreed definition. However, within this handbook they are used to describe two distinct, but related techniques. Full explanations are given below, but as an introduction, false seedbeds use tillage / cultivation[1] to kill the weeds while stale seedbeds use thermal weeding or herbicides for weed control.

3.1. The three 'golden rules'

There are three key pieces of scientific theory or 'golden rules' that underpin false and stale seedbeds.

1. Only 85-95% of seeds are dormant at any given time, but the 5-15% that are non-dormant, most, germinate (very) quickly;
2. Tillage is the most effective means of getting weed seeds to germinate;
3. Most weeds can / will only emerge from top five centimetres / 2" of soil.

3.2. The dormant and non-dormant weed seed bank

The weed seed bank (i.e., all the viable weed seeds contained within the soil) is a kind of time-machine for weeds (and other plants). It allows them to persist through time, even when the 'living plant' stage of their lifecycle is absent. Indeed, for most annual weeds, the seed bank is the permanant / main stage of their lifecycles, the living plant stage is ephemeral: a weed plant is just the seeds way of making more

[1] The terms 'tillage' and 'cultivation' (like false and stale seedbeds) do not have agreed international definitions. In GB, NZ, and AU cultivation refers to pre-planting soil management (ploughing, harrowing etc.,) while the term tillage is used infrequently. In the US and CA, tillage refers to pre-planting soil management, while cultivation refers to the use of machinery in growing crops to control weeds (which in GB, NZ and AU is called hoeing or weeding). At an international level and within the scientific literature tillage is used to mean pre-planting soil management (e.g., the 'Soil & Tillage Research' journal) so within this handbook the term tillage is used to refer to pre-planning soil management and the term cultivation is avoided with the aim of reducing confusion.

seeds! This is the opposite of perennial, plants, e.g., trees, where it is the living plant that is the permanant life stage and the seeds are something of a throwaway, tossed overboard with the slim chance that one of them may one day replace their parent. Therefore, for annual and biennial cropping weeds, it is the weed seed bank, not living weeds that are the heart / root of the weed 'problem'.

The technique plants and weeds use to make their seeds travel through time is dormancy. Dormancy is basically 'enforced sleep' i.e., dormant seeds wont germinate in conditions (e.g., warm, moist soil) that would otherwise make them germinate. While the internal workings of dormancy are pretty complicated, the outward effects are pretty straight forward. Dormancy stops seeds germinating all at the same time, so it staggers their emergence, across days, months years and decades. So, as the first golden rule states, only about 10% of weed seeds are **not** dormant and therefore are able to germinate.

3.2.1. Germination

Non dormant seed will however rapidly germinate when conditions are right. The right conditions that seeds detect to determine whether to germinate include:

- The correct **temperature** - not to hot and not tool cold;
- **Diurnal** (day to night) **temperature variation**, larger variations indicates the seed is close to the soil surface (the deeper in the soil the smaller the diurnal temperature variation);
- The presence of **nitrate** and other forms of mineral **nitrogen** which indicates a warm, moist soil with good oxygen levels as nitrate is produced by microbes breaking down organic matter. It also indicates proximity to the soil surface as oxygen concentration decreases with depth so microbial activity decreases with depth;
- **Sunlight** (or an absence of green filtered sunlight), indicating that there is little existing vegetation growing in the soil, and that the seed is close to the soil surface;
- **Water** - required for all plant growth;
- **Oxygen**, which is both required for growth, but also indicates that soil has been disturbed / tilled and also gives an indication of depth (as noted above) oxygen levels decrease with depth;
- Absence of allelopathic compounds, which both directly inhibit germination, and also their absence indicates an absence of existing vegetation;
- And other factors, often species dependent.

Any individual species may **not** require all of the above conditions to germinate, for example not all species respond to light, and they may respond in varying amounts to the conditions they do react to. However, the key message is that it is a mix of the above conditions that drive germination as a whole.

The reason weed seeds monitor and respond to the above conditions, is that most weeds have small seeds, so their seedlings are small, and they are easily out-competed by existing vegetation. They are also 'pioneer species[2]' that have evolved to be the first to colonize disrupted or damaged ecosystems. If they germinated among existing plants, there is a very high chance they will be out competed and die, so, they simply avoid germinating in such situations.

3.3. Tillage: the most effective germination promoter known to humankind

The above list of germination conditions explains why tillage is most effective weed germination promoter known - it ticks all the germination boxes:

- it increases temperature and diurnal temperature variation;
- it introduces oxygen into the soil, which stimulates microbes to breakdown soil organic matter into nitrates and other mineral forms of N;

[2] https://en.wikipedia.org/wiki/Pioneer_species

- it eliminates existing vegetation, eliminating the suppressive effect of green filtered light and the germination enhancing effect of direct sunlight;
- eliminating existing vegetation also reduces allelopathic compounds.

It is difficult to emphasise just how good tillage is at getting weed seeds to geminate - nothing that scientists can do in the lab come within a bulls roar - much to the chagrin of weed scientists.

The reason the effect is so quick, is because annual weeds are pioneer species, and germination is a fight to the death, in that whichever weeds germinate quickest are likely to have the competitive advantage, and therefore overtop and crowd out the laggards, who eventually die.

This is also why, after tilling a field, a carpet of green emerges, when before, nothing was germinating. But, that carpet of green only represents only 10% of the weed seedbank, i.e., the 10% that is not dormant, the other 90% is still deep asleep waiting for another year.

3.4. Suicidal germination?

The third golden rule is that weed seed can, and will, only emerge from the top 5 cm / 2" of soil. The reason for this is explained in Figure 3. It shows the relationship between the size (weight) of the seeds and the **maximum** depth of successful emergence. Depth of emergence is very firmly constrained by physics: the amount of energy and nutrients stored within the seed puts a hard upper physical limit on the amount of soil the seedling can grow up through before it 'starves' to death due to not getting any sunlight. As most agricultural and especially horticultural weed seeds are small, i.e., less than 5 mg most can only emerge from the top 5 cm / 2" of soil.

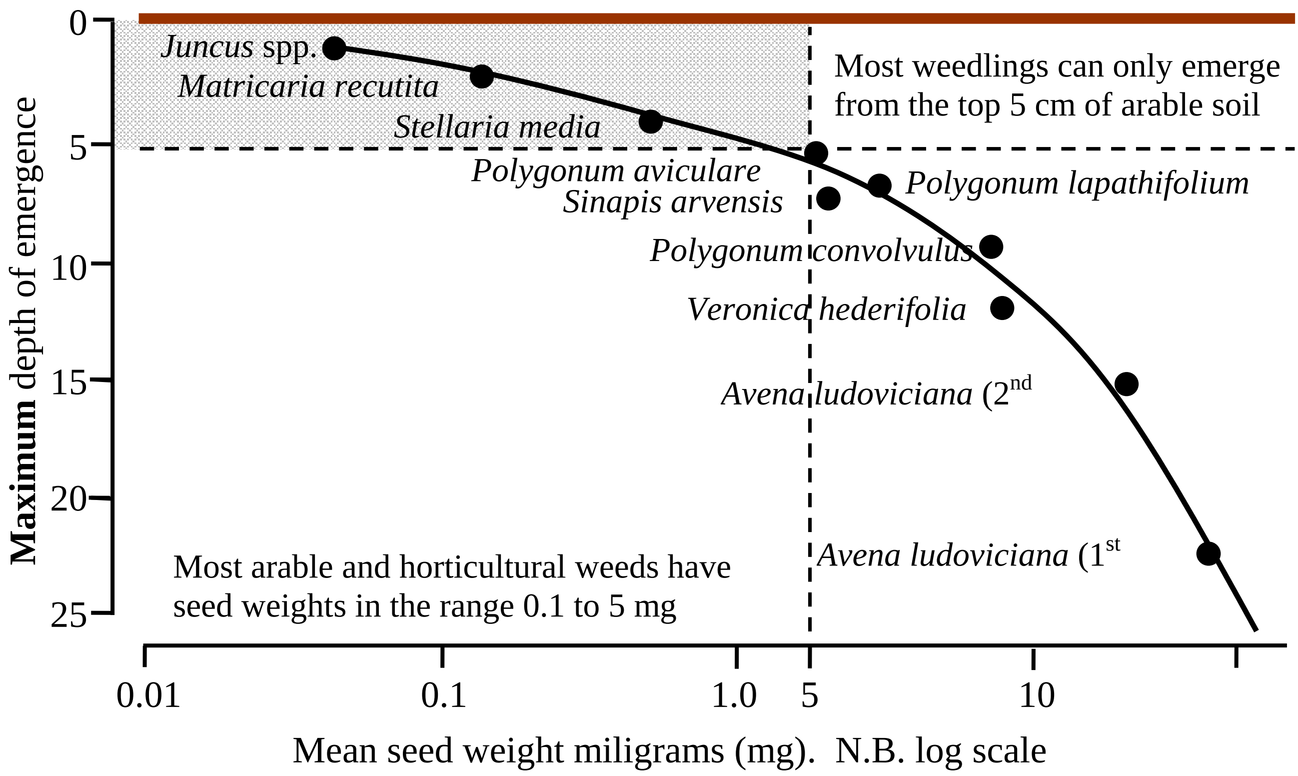

Figure 3. The maximum emergence depth of a range of weed species based on their seed weight. After Roberts, H. A., Ed. (1982). Weed Control Handbook. Oxford, Blackwell Scientific Publications.

However, this is the **maximum** depth of emergence, i.e., only 1%, say, of seed will successfully emerge from this depth, the other 99% that try, fail. What this means is that for 50% of weedlings to successfully emerge, they need to be at considerably less depth than this, e.g., 2 cm / 1". So in practice this means that the vast majority of emerged weedlings came from the top 7% of the plough layer, i.e., the top 1" / 2-3 cm.

And to reinforce the point of why the weed seedbank is so persistent, if only ~10% of seeds are non-dormant, throughout the whole plough layer, and only the seeds in the top 1" / 2-3 cm / 7% of the plough layer will try and germinate, that means only 7% of 10%, or 0.7% of the seedbank will germinate for each tillage operation.

And returning to the list of required germination conditions (section 3.2.1) nearly all of these tell a seed how far down the soil profile it is, i.e., is it close to the surface or buried at depth. As seeds can tell how close to the surface they are, they wont try and germinate, unless they are in striking distance, as to do otherwise would be suicidal. So not only can seeds not emerge from depth, they wont try to either.

3.5. Putting the three golden rules together

So, summarising all of the above:

- 90% odd percent of the weed seedbank (throughout the whole soil profile) are out for the count, but, like Arnie Schwarzenegger, they'll be back;
- of the 10% of the seedbank ready for action, only those in the top 5 cm / 2" are going to engage;
- but when given the right conditions, which means tillage, they will engage very rapidly, and emerge as a weed flush.

That is why you get a carpet of weedlings following tillage, time, after time, after time!

4. The practice of false and stale seedbeds

Non-chemical weed management is a bit like the martial arts - you study your opponent and use their strengths and weaknesses against them, and this is particularly true for false and stale seedbeds. The key is that:

- Weed seeds can only emerge from the top 5 cm / 2" of soil
- Non-dormant seeds will germinate very rapidly following tillage

False and stale seedbeds work, by getting the non-dormant seeds at the soil surface to germinate, then killing them, without bringing up more non-dormant seeds from deeper in the soil. Or put simply, grow the weeds, then grow the crop. Very simple, but very effective.

4.1. How to do it in practice

Implementing false and stale seedbeds is essentially a one-step addition to normal soil preparation practices. Soil is tilled to achieve the desired planting tilth, and then instead of sowing or planting immediately, sowing / planting are delayed to allow the weeds to germinate. It is how and when that the weedlings are killed that differentiates false from stale seedbeds.

4.2. False seedbeds

For false seedbeds (Figure 4) the seedbed is prepared ready for planting, (a), non-dormant weed seeds in the top 5 cm / 2” of soil germinate (b-c) and then emerge (c-d), weedlings are killed by tillage (e), the crop is then sown or planted (f) crop germinates and emerges (g).

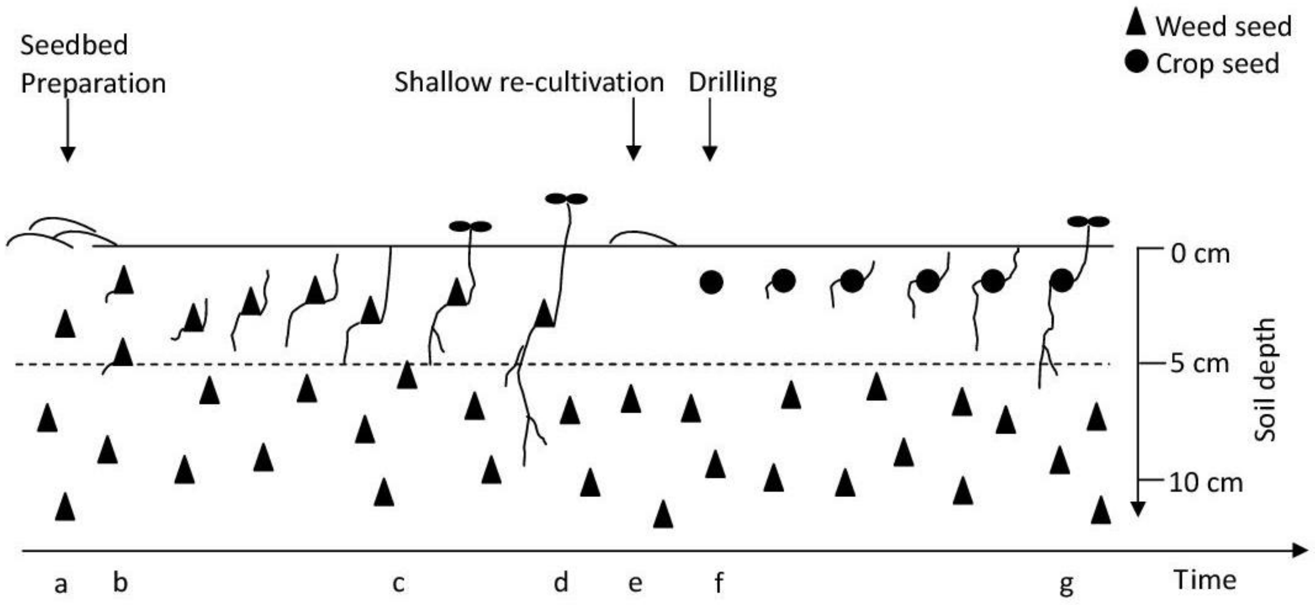

Figure 4. Illustrative scheme of a false seedbed.

4.3. Stale seedbeds

For stale seedbeds, the seedbed is prepared the same as for false seedbeds (a), non-dormant weed seeds in top 5 cm of soil germinate (b-c), the crop is sown (d), weed seedlings emerge (c-e), immediately prior to crop emergence (g) weed seedlings are killed without disturbing the soil (f), crop emerges (g).

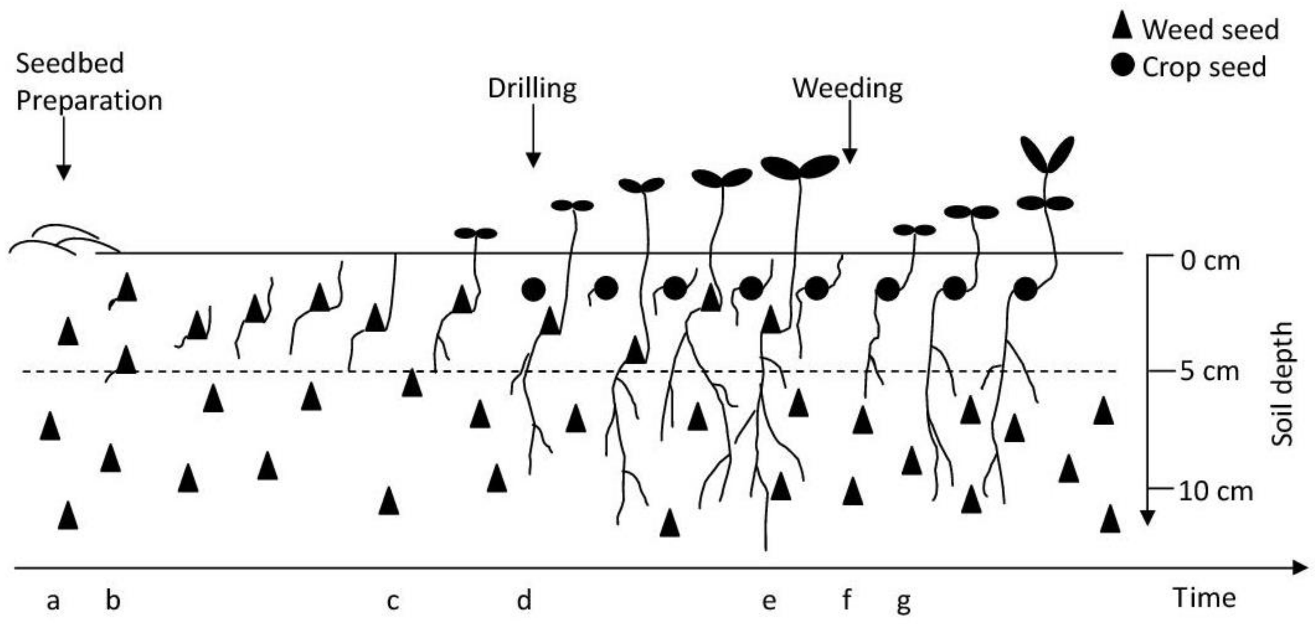

Figure 5. Illustrative scheme of a stale seedbed.

4.4. The importance of a 'perfect' seedbed

Regardless of whether a false or stale seedbed is used, if the seedbed is not in optimum conditions, e.g. too dry or cloddy, then germination will be reduced, and those seeds that did not germinate are then likely to emerge later in the crop. It is therefore vital that the original seedbed must be of the best quality possible, and if conditions are dry and suitable irrigation is available, then the soil should be irrigated sufficiently to ensure the weed seeds germinate.

4.5. The key differences between false and stale seedbeds

4.5.1. What's in a name

False seedbeds are so-called because the first seedbed is not the true seedbed as it is destroyed by tillage while stale seedbeds are so-called because the seedbed is no longer freshly tilled at the time of crop planting/sowing, rather it has aged or become 'stale' by planting time.

4.5.2. How weeds are killed

Next, the main differences between the two techniques are how the weeds are killed - tillage for false seedbeds and non-tillage techniques for stale seedbeds. For non-chemical weeding a thermal weeder, e.g. flame or steam is used, or where chemical control is an option a broad-spectrum herbicide, typically a quick acting contact, would be used.

4.5.3. Time of planting / sowing

The next difference is the when the crop is drilled (stale seedbeds are not typically used with transplanted crops). For false seedbeds, the crop is planted after the weeds are killed, while in the stale seedbed the crop is drilled into the emerging weeds.

4.5.4. Target crops

At a practical level both false and stale seedbeds can be used for any crop both sown and transplanted. However, the cost difference between them, especially when thermal weeders are used, mean in practice their use varies considerably:

- False seedbeds are practical and cost effective for anything that is sown or planted, from establishing pasture, through arable crops to vegetables.
- Stale seedbeds, implemented with thermal weeders are mostly the preserve of high-value, direct sown and especially slow germinating, vegetable crops, due to the high capital and running cost of thermal weeders. Where herbicides are used, their lower cost, makes them economical for a wider range of situations.

4.6. Critical knowledge to ensure success

While the basic concepts of stale and false seedbeds are pretty simple, there are a number of factors that are critical to their success.

4.6.1. Tillage depth for false seedbeds - the most critical key for success

One of the most common mistakes in implementing false seedbeds is that the re-tillage is too deep. Science tells us that 5 cm / 2" is the maximum depth of emergence for most cropping weeds. If the false seedbed tillage is deeper that this, it will bring up non-dormant, ungerminated seeds from deeper in the soil, which will then germinate. Deeper than 5 cm / 2" tillage therefore does not create a false seedbed, it creates a brand new seedbed. It is therefore mission critical that the re-tillage is as shallow as possible, ideally, 2 cm / 1" deep while killing as many weedlings as possible. This is beyond the ability of most standard agricultural machinery, so specialist equipment is needed, which is covered in section 5.1.

4.6.2. How long to delay planting

One of the most common questions about false and stale seedbeds is how long should the delay between soil preparation, killing the weeds and sowing or planting.

The length of time required varies depending on the time of year (which determines soil temperature), the weed flora, the crop species and if it is a false or stale seedbed.

The warmer the soil is the quicker weeds will germinate, and conversely the colder the slower the weeds will be. This varies considerable across the world, this has to be determined farm by farm even field by field, through experience.

Generally, most annual crop weeds germinate very quickly, but there are a few slowcoaches, which again can only be identified through local experience, and if slow germinating weeds are a problem, then extra time will be required.

The delay between ground preparation and sowing is generally shorter for stale, than false seedbeds as the crop is sown into the emerging weeds with the stale seedbed while for the false seedbed the weeds need to have fully emerged before being killed by tillage.

Crop species generally has the biggest impact on the duration of stale and false seedbeds as crops' emergence speed varies considerably, from a few days for the likes of radish in warm soil to a few weeks for carrots and parsnips in cool soil at the start the season.

So, the question 'how long should I wait' is the proverbial ball of string question - it depends on all the above factors. Having said that, typically one week would be a minimum between the last tillage pass and drilling for stale seedbeds, two weeks being typical between tillage and re-tillage for false seedbeds, with three weeks in cooler weather, and four weeks being the typical maximum wait.

4.6.3. Getting perfect timing for stale seedbeds

The aim of stale seedbeds is to kill the weeds just before the crop emerges, literally as little as 12 to 24 hours. Clearly this take perfect timing. There are three main ways to do this:

1. Inspecting the germinating seeds on a regular basis;
2. Accelerating the germination of small areas of crop;
3. Planting extra seeds and weeding as the first crop plants break the surface.

For al these techniques it is vital to ensure you take a representative sample of the field. It is no use just sampling in one corner by the gate - emergence there could well be later than the rest of the field due to more compaction and colder soil or shading from trees for example. You must have a number of sampling sites across the whole field especially if there is a lot of variation, e.g., slope, aspect, soil type, etc.

4.6.3.1. Digging up the seeds

Inspecting the germinating seeds obviously requires that you can find them in the soil. For large seeds, coated seeds and where precision drills have been used, this is not too difficult, while for other seeds and seeding techniques it can be nigh on impossible. The advantage of this technique is you get more warning as you can see when the seed coat breaks, then the root emerges and then the shoot wont be too far behind.

4.6.3.2. Accelerating germination

This works by warming the soil in a few sample sites around the field and as soon as the crop in the sample sites emerges then you know the rest of the field will be close behind.

The old recommendation for accelerating germinating is to place a sheet of glass just off the soil e.g., 0.5 mm / ¼" which then acts like a mini glasshouse warming the soil and thus speeding up the germination of the crop under it. If the glass sheet is placed directly on the ground it can solarise the soil and kill the seeds so you then don't get any warning at all. However, the obvious problem with glass sheets is that they are not very convenient, especially when they break. A better alternative is a square meter / yard of strong frost cloth, either spun-bonded or knitted, which can be rolled up and stuffed in a pocket and held in place with some tent pegs.

4.6.3.3. Higher seeding rates

This technique is based on sowing a slightly higher rate of seeds, e.g., 5 - 10% and then waiting for the first crop plants to appear and then weeding. This kills the first plants, but, the population should still be on target due to the higher sowing rate.

This is probably the least preferable of the three techniques, especially for vegetables and other crops with precise seeding rates, and because the first seeds to emerge are usually the strongest plants so killing them is not so ideal.

4.6.3.4. Inspection, inspection, inspection

And pretty obviously as timing is so critical for stale seedbeds, whichever of the above techniques are used they need to be inspected regularly. As the crop species have predictable germination rates, it is possible to have fewer inspections right after sowing, but as the expected date of emergence approaches then the field should be inspected at least once a day, and even twice a day for faster germinating crops. So for very fast germinating crops such as radish, inspections should start the day after sowing, while carrots can probably have 5-7 days grace before inspections start.

4.6.3.5. Being ready for immediate action

An a final reasonably obvious point is that as soon as the emergence monitoring system indicates that the crop is poised to emerge, weed killing should start immediately, not the next day. So it is vital to ensure the flamer or sprayer is ready to go at immediate notice and have a full supply of fuel or herbicide to hand. It is not the time when the crop is emerging to thing about getting the equipment out of the shed after winter and seeing if it works and then ordering fuel or herbicide!

4.6.4. The prerequisite for success: having the weed seed bank under control

While false and stale seedbeds can be exceptionally effective at controlling annual weeds they can't work miracles. The key prerequisite for success is that the weed seedbank is under control, i.e., the amount of seed in the bank is not excessive, and that there have not been large falls of weed seed rain in recent years. If there is a large weed seed bank and/or recent large weed seed rains, then all weed management techniques are going to have their efficacy significantly reduced, including false and stale seedbeds. Having said that multiple false seedbeds are really useful to reduce the weed seed bank.

Contrast Figure 2 on page 7 and Figure 6 below, both are carrot crops that have received the same false and stale seedbed regime, however, Figure 2 despite being a processing crop (i.e., low density) is practically weed free, while Figure 6 a fresh market crop (i.e., high density) is infested with weeds. The reason Figure 6 is full of weeds, is that the weed seed bank is both very large, and has been recently replenished by a large weed seed rain the previous season.

Figure 6. Carrot crop overwhelmed by fat hen / lambsquarters (Chenopodium album) despite using the same false and stale seedbed regime as Figure 2, the difference being due to the large size and young age of the weed seed bank.

The issue with large weed seed banks is that false and stale seedbeds, and many other weeding technologies can not get rid of 100% of the weeds, rather they achieve a reduction, sometimes a very large reduction, e.g., 99.9%, but rarely 100%. If there are 100 weeds per square meter / yard to start with then getting rid of 99.9% of them leaves 0.1 weeds per m^2 / $yard^2$ i.e., effectively none - i.e., the result in Figure 2. However, if there are 100,000 weeds per square meter / yard, to start with killing 99.9% leaves 100 weeds behind per m^2 / $yard^2$ - i.e., the result in Figure 6.

100,000 weeds per square meter is not an unrealistic amount. Figure 7 shows the correlation between the weed seed bank (no. of viable seeds counted in 1 kg of soil) and the number of weeds that were germinated under controlled conditions. One square meter of soil to 5 cm depth weighs approx. 125 kg, which at the highest weed seeds levels in Figure 7 equals about 120,000 seeds per square meter which is the situation in Figure 6.

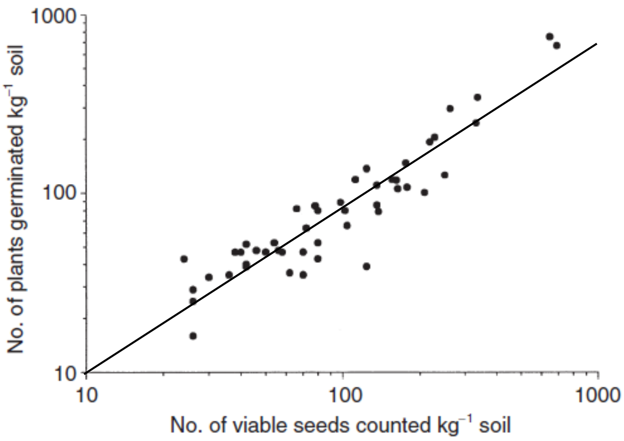

Figure 7. Number of viable seeds found in each of 48 individual soil samples, from Rahman, A., James, T. K., Grbavac, N. & Mellsop, J. (1996). Spatial distribution of weed seedbank in maize cropping fields. Proceedings of The 49th The New Zealand Plant Protection Society (Inc.) Conference, Nelson, New Zealand, 291-295.

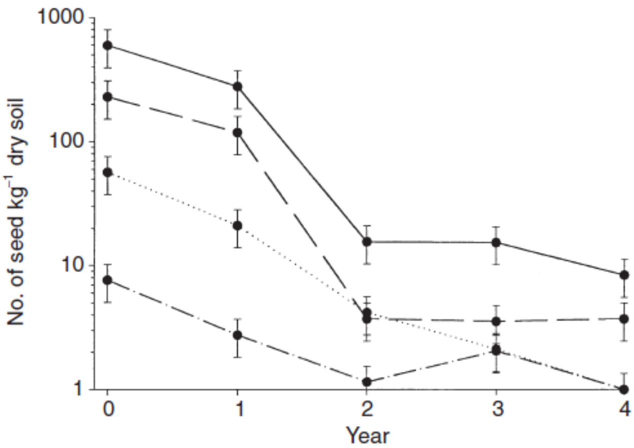

Figure 8. Decline in seed numbers of four weed species number of weed seedlings emerged versus the following monthly cultivation over a four year period **NB log axis.** From Rahman, A., James, T. K., Bourdôt, G. & Grbavac, N. (1998). Weed seedbank estimation, spatial distribution, decline and potential for predicting future weed populations. Plant Protection Quarterly, 13, 117–122.

Figure 8 shows the remediation of the situation in Figure 6, by the use of monthly fallow over four years, the size of the weed seedbank is reduced in the case of the most populous weeds from nearly 1000 to 10 seeds per kg soil. Monthly fallows will be quite damaging to soil, however, false seedbeds, as they till much less soil than standard tillage, are less damaging. Also as false seedbed tillage focuses on the surface seedbank, not the whole seedbank, the technique can significantly reduce the emergable seedbank in one season, if there are sufficient passes, e.g., three to five.

4.6.5. Stacking false and stale seedbeds

There is also no reason why only one false or stale seedbed should be used, it is perfectly possible to 'stack' them, e.g., one or more false seedbeds followed by a stale seedbed. Typically this approach is used where there is a large weed seed bank, there is plenty of time between crops, or for high value, poorly competitive direct-sown crops such as onions and carrots.

The normal approach would be to have multiple false seedbeds and finish with one stale seedbed, as following a stale seedbed with a false seedbed undoes some of the benefits, i.e., lack of soil disturbance, of the stale seedbed. At the same time, it is practical to 'stack' stale seedbeds with multiple passes to kill successive flushes of weedlings, before they get to big.

4.6.6. Non-tillage false seedbeds: not quite a contradiction, more a hybrid

Using non-tillage techniques, i.e., thermal or herbicides for transplanted, rather than drilled crops is a kind of hybrid between false and stale seedbeds. Essentially the non-tillage technique replaces tillage in the false seedbed system, with the crop being transplanted post treatment, generally immediately after treatment.

The reasons why non-tillage weed killing techniques may be used for transplants / false seedbeds, vary. If a lot of stale seedbeds are used, but few false seedbeds, then, having extra equipment for the false seedbeds may not be warranted. Alternatively, there may be a desire to avoid broader soil disturbance prior to transplanting, e.g., due to a large weed seedbank, though the transplanting itself will disturb the soil to some extent. And there may well be others.

4.6.7. Exceptions to the rule

As with practically everything in agriculture, your mileage will vary. And while false and stale seedbeds work exceptionally well for most cropping weeds, there are always exceptions.

While the vast majority of cropping weeds have seeds smaller than 5 mg and are therefore amenable to false and stale seedbeds, as Figure 3 shows there are weeds with larger seeds for which the techniques are less effective. For example wild oat (*Avena sterilis,* syn. *Avena ludoviciana)*, can emerge from 25 cm / 10".

Other species may not respond to tillage by germinating immediately. This may have multiple causes. For example, some weeds, such as nightshades (*Solanaceae*) have a temperature threshold for germination, below which none will germinate, while just above it large numbers will germinate. Where the initial tillage for false and stale seedbeds is implemented below the temperature threshold but soil then shortly warms up above the threshold, a large flush of nightshades can result.

Another example that may not germinate in response to tillage is subterranean (sub) clover (*Trifolium subterraneum*). Sub clover seed is larger than many other clovers, being in the region of 2-3 mm / 0.08 - 0.1" so they can emerge from deeper than the top 5 cm / 2" and they germinate in response to drying and wetting cycles, i.e., if the soil has dried out, and then there is a large amount of rain, sufficient to completely rewet the soil, sub clover will germinate solely due to being dry then wet.

4.6.8. Selectivity of thermal weeding - not all weeds are equal

Thermal weeding, both flame and steam, are unique in the way they kill and don't kill weeds. The popular 'test' of thermal weeding efficacy is the 'thumb print test' where a leaf is pressed between two fingers, and if it leaves a fingerprint this indicates the weed is dead. However, it is **not** the leaves that need to be killed but the weeds buds (meristems). The thumb print test is therefore a red-herring and, it is not possible, by visual inspection, to see if the buds have been killed. Weed death, especially for larger plants, can only be determined, by waiting a day or few, for the effects of the heat to show up in the stems and buds.

The next impact of it being the buds that thermal weeding needs to kill, to kill the plant, is that weed and crop species that have protected growing points can be tolerant, even resistant to thermal treatment. Species that fall into this heat tolerant / resistant group include all the monocots such as onions, maize, and grasses, and dicots, when they have reached sufficient size, that have stolons or rhizomes, e.g., as clover, rosette leaf forms, such as carrots, beet and dandelions, or have thick stems with the buds recessed into the stems, such as nightshades (*Solanaceae*) and wire weed (*Polygonum aviculare*).

Where there are a lot of grass weeds, thermal treatment is unlikely to completely kill all of them, even at cotyledon stage. And, where thermal treatment is regularly used instead of tillage for the false seedbed approach, populations of grass weeds are likely to increase considerably, especially those that reproduce quickly such as annual meadow grass / annual bluegrass (*Poa annua*).

In comparison, tillage kills all weeds at early growth stages, so has no such issues.

5. Machinery / equipment for false and stale seedbeds

Most standard agricultural machinery cannot successfully implement false and stale seedbeds due to the specific requirements of the techniques. This section describes the machinery required - some of which is simple enough for any mechanically competent person to build, others will need to be purchased or need specialist fabricators.

5.1. False seedbed cultivators

As highlighted in section 4.6.1, the critical factor for successful false seedbeds is that tillage depth must be no deeper than 5 cm / 2” and ideally is should be as shallow as 2 cm / 1”. At the same time it needs to achieve a high level of weedling mortality, and for vegetable production, 100% mortality is required due to the lower competitive ability of vegetables compared with arable crops.

5.1.1. Spring tine weeders

Spring tine weeders (Figures 9 & 10) go by a number of names including spring tine harrows, finger weeders, tine weeders and more. They are essential equipment for non-chemical weeding in arable crops, as well as being generally all-round useful tools, including being used for final seedbed preparation and also broadcast sowing a range of crops using pneumatic seeders. They come in a wide range of sizes from tractor width to 20 m wide, and there are many manufacturers to choose from.

Figure 9. Spring tine weeders - detail of frames and tines

Figure 10. Spring tine weeders - from small to very large.

Spring tine weeders can also be used for false seedbeds, but, while their depth of cultivation is shallow, indeed, it is hard to get them to till as deep as 5 cm / 2”, they rarely achieve 100% weed kill, with typically figures being lower, especially in sub-optimal conditions (i.e., wet and cold). Higher kill rates can be achieved by multiple passes, and this may be sufficient for strongly competitive crops such as wheat and triticale, for example, but it is likely to be inadequate for most vegetables.

On the positive side of the ledger, spring tine weeders are comparatively inexpensive on a working width basis, and as they can be used at high speeds, working rates are very good. As they can also undertake a range of other tasks, it is likely that arable farms pursuing a non-chemical or reduced herbicide regime will need one anyway, so using them for false seedbeds spreads the cost even further

5.1.2. Milling bedformers

Milling bedformers (Figures 11 & 12) are specialised vegetable tillage machines. A the front the have a horizontal axis rotor, typically with C or knife blades, in place of the typical L blades of rotovators / rotary hoes. At the rear is the component that makes the machine unique - a horizontal axis, reverse-rotating roller with a large number of stub tines, that has a raking effect which produces a very fine, level and optimally firmed tilth, especially small, direct-seeded vegetables. It is this rear roller that the ‘milling’ name comes from, as it ‘mills’ the soil into a fine, even, level, tilth.

Figure 11. Milling bedformer

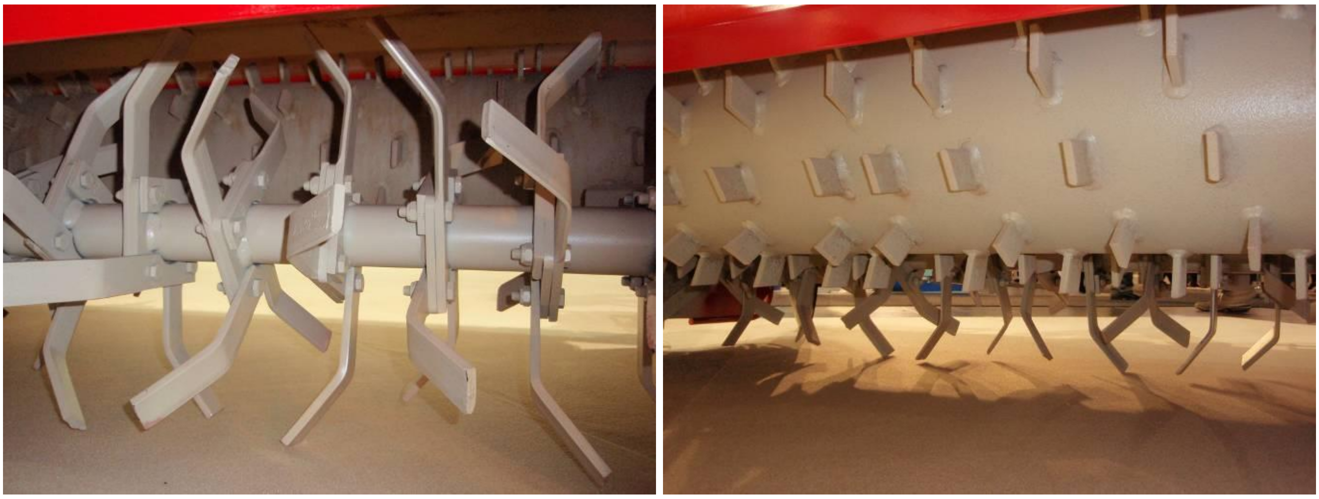
Figure 12. Milling bedformer, front rotor (left) reverse-rotation, stub-tine, rear- roller (right).

Once beds have been formed, milling bedformers can also be used to implement a false seedbed, as they are able to till the pre-formed beds to a very shallow depth, i.e., < 5 cm / 2”, produce an optimal seedbed, and achieve 100% weed kill, even with larger weeds, e.g., 10 cm / 4”.

The disadvantage of these machines, is even when the beds have been pre-formed, they are comparatively slow, e.g., < 4 kph / 2.5 mph, they required PTO power and have a high capital cost. However, their value in vegetable systems for tillage / producing optimal seedbeds is such that, that attribute alone often more than justifies their cost.

5.1.3. Specialist false seedbed tillage equipment

Spring tine weeders and milling bedformers are the only off-the-shelf machinery that are viable for tilling false seedbeds, beyond that, specialist equipment is required.

5.1.3.1. Roller undercutter false seedbed tillers

Roller undercutters (Figure 13) consist of a light-weight undercutter bar, attached to a smooth roller. The rollers primary purpose is to achieve very accurate depth control of the undercutter bar, but it also has the benefit of creating an excellent planting tilth.

Figure 13. Roller undercutter false seedbed tiller, with front and rear undercutter bars plus side shields to retain bed sides. Design and photos copyright © Steam Weeding Ltd. 2015.

The undercutter bar can be placed before or after the roller to achieve different outcomes. When before the roller, the bed is left in a firm condition, ideal for planting and sowing and also encouraging further weed strikes. However the weeds that have been undercut are then also firmed in, so it works best on small weeds. When the rear undercutter is used, the tilth is left loose, which can help retain moisture (a ‘dust mulch’) which also tends to inhibit further weed seed germination as the surface is dry. This can be useful if crops are then planted / sown into the loose soil and firmed in as the crops are well anchored but the remaining soil should produce fewer weeds. Also when there are larger weeds, the rear undercutter is more effective as instead of the weeds getting firmed back into the soil by the roller, they are typically left on the surface.

Key advantages of the roller undercutter are that it is low cost to purchase and operate as it is a very low draft machine. It can also be operated at high speeds, e.g., 10 kph / 6 mph, and is a great companion to milling machine bedformers as the latter can set the beds up, while the former can then undertake the false seedbed tillage at much higher speed, so making better use of capital equipment.

The key problems with the roller undercutter is that horizontal bars, especially those operating at very shallow depth, readily collect plant residues and other field trash, which can quickly block up the bar. While this can be easily cleaned by putting the machine on the headland and gently running it backwards to scrape the residues off, this is not practical for larger scale operations, so the roller undercutter is best suited to small scale market garden type setups. They are also intolerant of stony soils, as the bar tends to jump out of the ground when impacting larger stones, or large quantities of stones.

It is also possible to just use a standard vegetable undercutter bar, however, accurate depth control is much harder unless the tractor has exceptionally sensitive draft control, and even then, forward speed will be limited due to the interaction of draft and speed and also the draft systems reaction time.

5.1.3.2. Roller rod-weeder false seedbed tillers

Roller rod-weeders are based on the American rod weeders used for dust mulching in the drier parts of the country. These consist of a length of steel bar, round, square or hexagonal cross section, that is dragged through the soil surface to kill weeds and break the soils capillary action, thus retaining soil moisture (Figure 14). The rod can either be simply free to rotate, or ground driven as in Figure 14. The key advantage of a rotating rod, compared to an undercutter bar, is they are much less prone to suffer residue build up, especially the driven forms.

Figure 14. American rod weeder (left), rod weeder built into spring tine cultivator (right). Design and photos copyright © Steam Weeding Ltd. 2015.

Figure 15. Roller rod-weeder (left), in operation (right). Design and photos copyright © Steam Weeding Ltd. 2015.

Roller rod-weeders, are therefore simply roller undercutters with the undercutter bar substituted by a rod as in Figures 14 & 15. However, to cope with wetter soils, higher residue levels, stones and less-loose soil the rods need to be powered, e.g., via a hydraulic drive. Therefore there is a trade-off between increased effectiveness but higher cost, and reduced working rate due to the powered rod. Typically powered rod rotate against the direct of travel for greatest effect.

One downside of the rods is due to their thickness, typically 3 cm / 1" they have to go deeper to ensure they cut through the soil not roll over the surface, which means they are tilling the entire top 5 cm / 2" of the soil while the undercutter blade is half that depth or less. Theoretically this means they may be bringing up ungerminated non-dormant weeds and therefore be less effective than bars, but extensive field use has shown no such problems.

Also, while the roller rod-weeder in Figures 14 & 15 is built into a spring tine cultivator, this is not essential, and stand-alone rod and roller systems, akin to the roller undercutter in Figure 13 are also viable machines.

5.1.3.3. Twin roller and A blade sweeps false seedbed tillers

The third false seedbed tiller desing approach uses A blade sweeps, as used on interrow hoes, as the weeding tool Figure 16. These combine the advantages of both roller undercutter and rod-weeders. They are simple, non-powered, with low draft and high operating speed like the undercutter, but they are able to cope with residues and a moderate amount of stones, like the rod-weeder.

Figure 16. Twin roller false seedbed tiller. Design and photos copyright © Steam Weeding Ltd. 2015.

The issue with using sweeps compared with a rod or an undercutter bar is the length of bed they occupy: rods and bars occupy only a few centimetres / couple of inches of bed length while a sweep often occupies 30 cm / 1' bed length. In addition a single row of sweeps cannot cover the full soil surface so two rows are needed. Therefore the length of bed required for a set of sweeps is typically about 1 meter / yard. With the sweeps spread over 'such' a long run of bed, it is impossible to accurately control their depth using just one roller (as is done with rod and bar machines). Two rollers are therefore required, but on the up-side, this provides ultimate depth control, and a really nice tilth as well.

The one area sweep based false seedbed tillers are weaker than rod and undercutter machines is their ability to kill larger weeds as the second roller tends firms the cut weeds back into the soil giving them a chance to re-root.

5.2. Stale seedbed machinery - thermal weeders

If herbicides are not an option for stale seedbeds, the only non-chemical option are thermal weeders.

5.2.1. The long list of failed thermal weeding ideas

All but one thermal and related physical techniques have been tried over the years for stale seed beds, including lasers, microwaves, UV light, electrostatic electricity, hot water, focused sunlight, dry ice ($C0_2$), liquid nitrogen, and more. None of them meet the criteria of being practical, effective, reliable, economic and safe. The only approach not tested is ionising radiation due to its very obvious safety problems. The only types of thermal weeder that have proved to be viable are flame weeders and steam.

5.2.2. Flame or steam?

In most situations flame weeders are preferred over steam weeders for stale seedbeds. This is because producing steam in an agricultural setting is difficult as the standard pressurised steam boiler is unsuitable, or worse lethal if not correctly used and maintained. There are direct-fired steam weeders that are purpose designed for agricultural use, but these are still more complex than flame weeders plus steam weeders use large amounts of water. The only time that a steam weeder may be preferred over a flame weeder is where there is a fire risk (direct-fired steam weeders have a very low fire risk, flamers have an obviously extremely high risk of igniting combustible material) and/or where using large amounts of LPG or propane as the fuel is problematic (most steam weeders use diesel as the fuel and flamers use LPG). N.B. This choice only relates to stale seedbeds for direct sown crops, the choice between steam and flame in other situations, e.g., perennial crops, is quite different.

5.2.3. Flame weeders

Flame weeders are therefore the best thermal weeder for stale seedbeds in 99% of situations. They are also a very old technology having been used in agriculture from the 1800s. They effectively died out with the advent of herbicides in the 1940s, but, with the expansion of organic agriculture in the 1980s, they have had a renaissance such that there are now a wide range of machines available, for example see Figures 17 18 & 19. The two main approaches are either flaming the whole bed, or just the crop rows. Row flamers require row spacings above 40 cm / 15” to make sense, so for narrower rows spacings whole-bed flamers are typically used.

Figure 17. Row flamers, single bed (left) and multi-bed (right). Design and photos copyright © Steam Weeding Ltd. 2015.

Figure 18. Bed flamers with longer hoods.

Figure 19. Bed flamers with shorter hoods.

Choosing the best flame weeder and understanding their design principles is a specialised topic beyond the scope of this article, but key issues to consider are:

- **Fuel type**: Practically all flame weeders run on LPG (propane / butane mix) or pure propane. Pure propane is preferable due to its much lower boiling point than butane which means in LPG systems the propane comes off first leaving the butane behind (fuel separation) which wont come out of the bottles when they are cold.
- **Fuel system**: the two choices are liquid or vapour takeoff. Vapour take off is the dominant system as is simpler but it suffers from icing up of the bottles due to the very high take-off rate, which requires a much large quantity of fuel to be carried. Liquid take off is more complex but eliminates the bottle icing problem meaning less fuel has to be carried and there is no issue with LPG fuel separation. Many of the better quality newer flame weeder designs now use liquid take off.
- **Control system**: How simple is the control system? Single on-off switch or multiple controls? Avoid systems where the fuel hoses travel to a control system in the tractor cab - a hose leak represents a major health & safety hazard even if the leaking fuel does not ignite.
- **Ignition system**: is ignition automatic, even in the event of blowout or is it manual. Manual lighting can be (very) hazardous.
- **Hood design**:
    - **Hood length**: Longer hoods are generally better as they achieve greater heat transfer, but are more unwieldy in the field, especially on small headlands.
    - **Wind susceptibility**: Many hood designs are open front and back, or with ineffective baffling, so that in windy conditions, efficacy is much reduced and operation may only be possible driving into the wind.
    - **Adjustability**: can the hood height be adjusted for different height raised beds, and/or use on ridges (e.g., ridge grown carrots or for dehaulming potatoes).

5.2.3.1. Determining operating speed

Determining the correct operating speed, and therefore 'thermal dose' (equivalent to herbicide rate) is critical to ensure all weeds are killed, but without wasting fuel and time. While there has been a range of research in this area, it has proved impossible to specify general operating speeds / thermal dose due to the large variation in efficiency among flame weeders and also the large variation among weeds in the amount of heat required to kill them, both among species and sizes / growth stages.

The traditional method of testing if a flame weeder has done-the-job is the 'thumb print test'. This is where a leaf from a plant that has just been flame weeded is pressed between thumb and finger and if a darker green thumb print can be seen in the leaf then the weeder has done the job. However, the thumb print test is a complete red herring as it is not the leaves that have to be killed but the weeds meristems / buds, because if the buds are not killed the weed will simply regrow new leaves (see also section 4.6.8).

Therefore, there is only one way to determine the correct speed for flame weeding and that is an on-farm trial. This has to be done each time a field has to be flamed as the correct speed can and will vary from field to field due to different weed flora, temperature, soil conditions and other factors. The same flamer also has to be used for the test and the actual weeding.

A day or two before a field is due to be flame weeded, a number of test runs at different speeds should be conducted over a suitable length of ground, e.g., 20 meters / yards for each of a range of speeds, e.g., 2,3,4,5,6 kph/mph. A day later the plots are viewed and the plot with the fastest speed with 100% weed kill is the optimum speed. However, as the weedlings are typically growing quite fast, and therefore require more heat / slower speed, and to build in a margin of error, the next slowest speed is used. See also section 4.6.8 about determining weed death.

Although the optimum speed will differ for every field and crop and for different flamers, once enough experience has been gained for a particular weeder on a particular farm then a set of ready-reckoner type optimum speeds for a range of situations can be developed and the speed test only used if there is doubt about the ready-reckoner speeds.

6. Conclusions

Stale and especially false seedbeds are amount the most effective, simple, quick and cheap means of non-chemical weed management for crop and pasture establishment. The key issue is that to be the most effective specialised machinery is required and they have to be used as part of an integrated weed management system - they cannot control all weeds on their own. But, when used as part of a holistic weeding system, the level of weed control that can be achieved without chemicals can be as good or better than that achieved by herbicides.

One of the outstanding questions is the different impact on future weed germination between false and stale seedbeds. Some producers are sure that there is less additional weed germination where stale seedbeds have been used, while others think that a couple of false seedbeds exhausts the germinatable weed seedbank and fewer weeds emerge later in the crop. So despite the techniques being well proven on farm, there is still a need for research into the detailed impacts on the weed seedbank and future weed seed germination.