The final frontier: Non-chemical, intrarow, weed control for annual crops with a focus on mini-ridgers.

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Permanent Agriculture and Horticulture Science and Extension

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1. Summary

- Controlling weeds non-chemically in the interrow is now a straightforward task due to modular interrow hoes and automatic tractor and implement steering systems.
- The intrarow, and especially close-to-crop-plant weeds, are now the final frontier for non-chemical weeding in annual row crops.
- There are two main approaches to intrarow weeding:
  - 'discriminatory' (high tech) weeders driven by computer vision or sensors that weed around crop plants:
  - 'non-discriminatory' (low tech) weeders where the crop is resistant / tolerant to the weeding technique while the weeds are susceptible.
- There are pros and cons to both techniques, as they suit different situations, but a key and inherent limitation for discriminatory machines is they cannot kill close-to-crop weeds, while non-discriminatory weeders can.
- Deciding among non-discriminatory weeders requires an understanding of how they kill weeds, viz: uprooting, severing / breaking and burial.
- Different tools kill weeds by these three modes in different proportions and with varying aggressiveness. Non-discriminatory tools also handle soil and weather conditions (texture, compaction, stones, wet vs. dry) very differently. It is therefore essential to correctly match the tool to the situation.
- However, of all the non-discriminatory weeders described, including finger weeders, torsion weeders, vertical spring tine weeders, and thermal weeders, the mini-ridger stands out as having a great combination of simple engineering, working in a wide range of crops and weeds, handling diverse soil conditions and maintaining a high weed mortality in wet conditions, and ability to reliably achieve 100% weed kill, including close-to-crop weeds.
- The key issue for mini-ridgers is it is impossible to tell in the field if the burial depth will kill the weeds, unlike the instantly obvious effects of other weeders. The FFC has therefore undertaken preliminary research to determine a rule-of-thumb for minimum burial depths.
- Initial indications using potting mix are considered to require burial depths considerably in excess of field experience, however, they do cast doubt on the idea of timing weeding operations at the white thread stage, particularly where the majority of weed death is caused by burial. The FFC will be undertaking field trials in the 2014-15 season to build on these results.

2. Introduction: The interrow is under control

Non-chemical weeding machinery has made huge advances over the last couple of decades, particularly compared with the machinery in use before the widespread uptake of herbicides in the 1950s. Out of all the great diversity of machines and techniques that have been tried, two approaches stand out as the foundation of modern interrow hoeing in annual crops:

- First, the development of modular parallelogram tool frames (Figure 1), that have allowed hoes to achieve excellent depth control across a wide range of widths, including individual toolbars in excess of ten meters, and multi unit machines with total working widths in the 25 meter range.
- Second, GPS and computer vision steering systems for both tractors and implements, which have transformed interrow hoeing from a highly specialised and mentally demanding job, often requiring mid-mounting on tool-carrier tractors and top-end drivers, to 'just' another standard tractor job using three-point mounted equipment.

Figure 1. Standard design of modern interrow hoe using modular parallelogram toolframes (red) being steered by a computer vision guidance system (green).

These two technologies have revolutionised interrow hoeing from being a task only undertaken when there is absolutely no other alternative, to one that can fit alongside herbicides in the toolbox as an equally effective and even cheaper weed control option. Controlling interrow weeds without herbicides is now a straightforward and reliable task thanks to autosteer and modern interrow hoes. The action has therefore moved to the intrarow (within the crop row) and especially the 'close-to-crop-plant' weeds that exert the highest competitive effect against the crop (due to their proximity to individual crop plants). However, while GPS, computer vision and modular hoes have made interrow hoeing straightforward, intrarow weeding is a much tougher challenge.

3. The final frontier: the intrarow and close-to-crop weeds

There are two main approaches to dealing with intrarow weeds:

- 'Discriminatory' weeders (high tech);
- 'Non-discriminatory' weeders (low tech).

Discriminatory weeders (high tech) are powered by some kind of 'intelligence' that allow them to identify what is a crop plant and what is a weed and therefore 'discriminate' between them. They then apply an aggressive weeding technique, e.g. hoe blade or flame to kill the weeds, but, if they get it wrong and misidentify a crop plant as a weed, then the weeding technique will kill the crop plant.

Non-discriminatory weeders (low-tech) don't have the 'intelligent' identification system of the high tech approaches, instead, they rely on the crop plants having a (much) greater resistance / tolerance to the weeding technique than the weeds; they then apply the weeding technique equally to both crop and weeds at the same time, with the result that weeds are killed but the crop survives.

4. Discriminatory weeders

Discriminatory weeders use two means of discriminating between crop and weed plants: (1) computer vision systems (2) sensors such as wands and light beams.

4.1. Computer vision

Computer vision systems are truly NASA grade technology - trying to differentiate between lots of similar, small, green, crop and weed plants against a highly variable background of soil, over a wide range of lighting conditions, in an agricultural setting has only recently become possible. The fact that only a handful of people / groups have actually developed machines that are effective in real-world farming, while many more have tried and failed, indicates how difficult it is. For example videos of these machines see http://www.garford.com/products_robocropinrow.html, https://www.youtube.com/watch?v=bhdeCk5PJGU, https://www.youtube.com/watch?v=qeYyWiLfiYw, https://www.youtube.com/channel/UC01nc4j8eSKXv_jIqIqXPnA (This is neither an endorsement of these companies nor a non-endorsement of other companies with similar products).

4.2. Sensors

The sensor based systems using light beams, wire wands or nudge bars, and are therefore technically simpler than the computer vision systems (no computers or cameras), but the crop plants needs to be significantly bigger than the weeds so the sensor can detect them but detect the weeds. Once a plant is detected, then the weeding technique / mechanisms is typically no different from the weeding tools used on computer vision systems - indeed the same weeding mechanism could be attached to either a computer vision or sensor crop plant detection system. The weeding mechanisms typically consist of small horizontal blade hoes that are moved in and out of the intrarow, though there are a number of other, often quite innovative, techniques such as Garford's kidney shaped rotating hoe and VisionWeeding's micro-flame banks.

Sensor based systems are also used in perennial crop (e.g. pip fruit, vines, bushes, etc.,) intrarow (under plant) weeders. For an example of a sensor based system for annual crops see http://www.plantdetectionsystems.com/ and perennial crops in Figure 2.

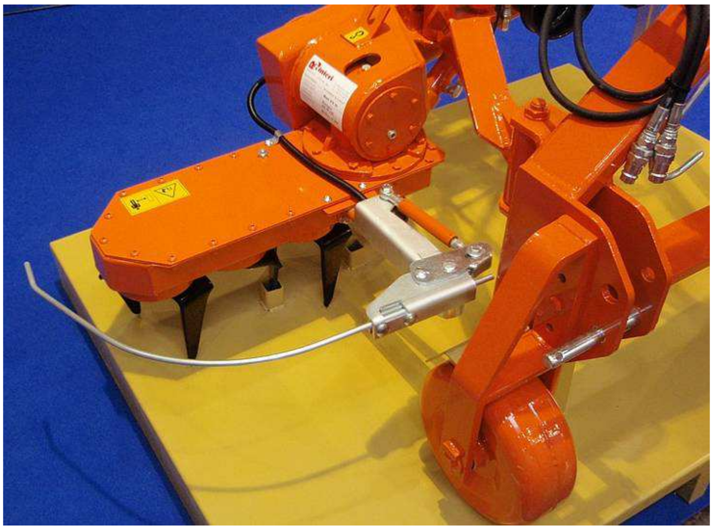

Figure 2. Perennial crop intrarow weeder (power harrow type) with sensor wand to the guide weeder around plants and posts.

Both computer vision and sensor based weeders achieve the same overall weeding job, as the weeding tools themselves are the same. The key difference is that computer vision systems can work with smaller crop plants and other situations where physical sensors cannot differentiate weeds from the crop (e.g. the weeds are as large as the crop). The trade off for the greater abilities of the vision systems is a higher (sometimes much higher) capital cost and complexity (e.g. repairs require a computer technician, not a hammer). Overall, one approach cannot therefore be said to be better than the other, rather, it is a case of horses for courses and matching the technology to the individual weeding situation, production system and its economics.

4.3. Machine vs. operator intelligence

A key point about discriminatory weeders, like herbicides, is that the smarts that make them work are provided by their creators (engineers for machines, biochemists for herbicides). The amount of smarts the end user therefore has to supply is pretty limited, some initial setting up, and then 'just' driving the machine up and down the field. This means that operator skill has a lower impact on the outcome, but that is paid for in higher capital costs. In contrast many non-discriminatory weeders require considerable skill in setting up by the operator and constant monitoring and adjustment to ensure optimum results. Skilled operators are therefore essential, but the capital cost of the machinery is lower.

4.4. Discriminatory weeds *cannot* control close-to-crop weeds

However, and this is the big however, due to the nature of the weeding technique, the really critical close-to-crop weeds cannot be killed by discriminatory weeders, because the weeding tools will kill the crop if it gets to close to them, so there has to be a 'no-weeding zone' directly around the crop plant. This is where low tech / non-discriminatory tools, somewhat surprisingly, have an advantage.

5. Non-discriminatory weeders

Compared with the mostly convergent designs of discriminatory weeders, non-discriminatory weeder designs are highly divergent because there are a multitude of ways of creating a machine that will kill weeds but not crop plants. It is not therefore possible to cover all the many different designs in this article, but, the major / widely applicable approaches are outlined below. Importantly, to be able to compare the pros and cons of different designs it is vital to understand how different machines / weeding techniques kill weeds.

5.1. How non-discriminatory intrarow weeders kill weeds

There are three fundamental techniques whereby all mechanical weeding machinery kills weeds. These are:

- Uprooting;
- Severing / breaking;
- Burial.

Uprooting leaves weeds mostly intact, i.e. the foliage and roots are still joined by an intact stem, though some root loss and leaf / upper stem damage / loss may occur. Weed death then occurs due to the plant no longer being able to absorb water through the exposed root system, and it therefore dies through desiccation. To be effective, uprooting therefore requires at least dryish soil and in particular, dry weather conditions, otherwise the weeds may be able to re-root before they are desiccated, and therefore regrow.

Severing / breaking is where the weed is cut or broken at, or close to, the hypocotyl (in dicots) or mesocotyl (in monocots) (the region of stem below the cotyledon leaves and above the roots). The hypo/mesocotyl, is akin to the neck of an animal in that severing, or breaking it, separates the water and nutrient gathering system of the roots, from the photosynthesising leaves, which means the plant is no longer able to grow, and therefore dies. If the stem is broken rather than severed, the damage needs to be sufficient to stop the phloem and/or xylem (vascular system) working.

Severing or breaking the weed close to, e.g. less than 1 cm, from the hypo / mesocotyl also generally results in plant death, as there are insufficient roots or stem left to allow the weed to survive. However, if the weed is larger and does has sufficient reserves, then it has the potential to regrow.

Severing / breaking of the hypo/mesocotyl is instantaneously lethal for small weeds so it is effective regardless of environmental conditions. However, cutting and breaking the roots or stem close to the hypo/mesocotyl is an aggressive form of uprooting, so it therefore results in higher weed mortality in dry than wet conditions. However, in reality , it is very difficult to consistently sever or break the hypo/mesocotyl of all weeds present in a field. So even with weeding techniques (e.g. horizontal knife blades) whose principle aim is to sever weeds at the hypo/mesocotyl, most end up being severed close to, but not through, the hypo/mesocotyl and are therefore technically uprooted, so dry soil and weather are required to achieve maximum weed death.

Some weeders with a very aggressive weeding technique, e.g. interrow brush hoes, kill by severing and breaking, but in an extreme form where the weeds may be cut into multiple parts and broken throughout their roots and leaves. This generally results in much higher mortality than simple cutting tools such as knife blades, especially for larger weeds.

Burial is where the intact weed is covered by a soil layer thus blocking sunlight from reaching the leaves and therefore killing the plant. To be effective the soil layer / burial depth needs to be sufficient to prevent the plant growing up through the soil to regain access to light. Burial is therefore mostly independent of soil and weather conditions, i.e. it is as effective in wet conditions as dry, as the plant is intact, the exception is where there is sufficient rain to wash the soil layer off the plants allowing them to restart photosynthesis.

5.2. Matching weeding technique to the situation

Most non-discriminatory intrarow mechanical weeders kill weeds through a combination of uprooting, severing / breaking and burial. Different weeders use different proportions, and levels of aggressiveness, of the three techniques, which, in turn, determines how effective they are in any given situation. This means no one weeder is 'better' than others overall, as some will excel in some situations but give poor results in others. The weeding techniques therefore need to be matched to a number of variables including:

- Weed size;
- Crop size;
- Weather conditions (wet vs. dry);
- Soil conditions:
    - Temporary soil conditions:
        - Soil moisture;
        - Tilth.
    - Permanant soil conditions:
        - Texture;
        - Stoniness.

The permanant soil conditions of texture and stoniness will completely rule some weeders in or out as they cannot deal with some situations, e.g. stones. The rest of the variables will all need to be considered on a case by case basis. However, it is unlikely to be economically viable to purchase every possible weeding tool in case it may be the best, so, the usual compromises have to be made to choose an optimum set of weeders or just one weeder, that will achieve the best result overall.

5.3. Thermal weeding

And, to complicated matters, thermal weeding, i.e. flame and steam weeders, add a fourth dimension to this mix as they kill weeds through heat rather than mechanical action.

Thermal weeders control weeds by killing all of the aerial meristems / buds (i.e. above the hypo/mesocotyl) and/or by killing the phloem in a complete ring around the hypo/mesocotyle (akin to ring-barking a tree). Thermal weeding is therefore akin to severing / breaking the hypo/mesocotyl in mechanical weeding (above), but if not all of the buds are killed, then it is akin to cutting the stem close to the hypo/mesocotyle, and so, if the weed has sufficient reserves (especially bigger weeds) then it can regrow.

If the thermal treatment kills all the aerial buds of most species of weeds when they are small, then the plant will die regardless of environmental conditions, but, if not all buds are killed, the plant is more likely to die in hot dry conditions and survive in moister conditions. The exception to this are plants that can regenerate true stems from true roots, but even among the weed species that can do this, most cannot do it at the seedling stage.

There is also a widely held misunderstanding (including in research and extension publications) about the 'thumb print test' where, after thermal treatment, a leaf is pressed between thumb and finger, and if a fingerprint remains, then the thermal weeding has worked. This is incorrect as it is the buds that have to be killed by the heat not the leaves, and buds require a longer treatment time to kill than leaves as they are protected in leaf axils. This means, at best, the failure of a leaf to take a fingerprint, means that there was also insufficient heat to kill the buds, but just because a leaf takes a print, does not mean the buds are dead. The only sure-fire way to determine the treatment speed, is to undertake a speed test a day or two before treatment is required, whereby a decent length of crop, e.g. 10 meters is treated at one speed, then another 10 meters 1 kph faster, over say, five speeds, and then checked for weed death the following day. To provide a margin of error, a slower speed (e.g. 1 kph) than the speed that achieved 100% kill is then used.

6. The most common, non-discriminatory, intrarow, weeders

6.1. Finger weeders

Finger weeders (Figure 3) work by breaking up the soil in the intrarow thereby uprooting, breaking, and burying weedlings. There are a very large range of options on the basic design, including different diameters / sizes, a wide range of materials used for the weeding fingers, from steel, through a range of plastics, fabric reinforced rubber and even brushes. This means that the weeding action can be varied from very aggressive (amplified by higher speed and down pressure) to exceptionally gentle. As the weeders are ground driven, only require a simple pivot depth control (not parallelograms), they have a reasonable latitude in adjustment accuracy (i.e. if they are not perfectly set, they will still achieve a good result), and they can work in a wide range of conditions (especially across the many different designs), they are one of the most popular intrarow weeders.

However, they are most effective against cotyledon stage weeds, and work best in dryer soil conditions and drying weather to help kill uprooted but undamaged weeds. They also have reduced effectiveness in stony soils. In optimum conditions weed kill can be about 85% but that can decrease significantly in sub-optimal conditions (wet soil and weather).

Figure 3. Finger weeders.

6.2. Torsion weeders

Torsion weeders (Figure 4) also work by breaking up the soil in the intrarow, but with more of a shattering effect than the mixing / churning effect of finger weeders. Also like finger weeders they are most effective against cotyledon stage weeds, and rapidly loose their efficacy as weeds grow beyond two true leaves. They also require loose level soil and only work in dry soil as the shattering effect does not work when soil is plastic. They are also unable to penetrate hard soil or be effective where there are stones. While they can be quite effective, they require precise setup, as only small differences in both vertical and horizontal placement can result in very large variation in the aggressiveness, from no effect at all to killing the crop. Very good depth control and steering are therefore required. In compensation, the tools are very simple - just shaped spring steel rod, so are cheaper than finger weeders (though more expensive parallelogram depth control systems are required). The summation of this means that maximum weed mortality is around 75% and it is often much lower.

Figure 4. Torsion weeders

6.3. Vertical spring tine weeders

The most common / standard vertical spring tine (spring steel wire) weeders are spring tine harrows (Figure 5) however, these are normally too aggressive for row-crops (i.e. cause crop damage) while at the same time they do not have a sufficiently intensive weeding action within the crop row. They are therefore generally of limited use for focused intrarow weeding.

Successful intrarow weeding with vertical spring tines therefore mostly requires dedicated equipment. This includes designs such as the rotary spring tine weeder (Figure 5), the vertical spring tine oscillating weeder (Figure 6) horizontal axis rotating spring tine weeder (Figure 6) plus many more designs on this general theme of vertical spring tines. These machines are best suited to thin upright crops such as maize/sweetcorn, leeks, and cereals, while they can cause significant damage to leafy spreading crops, e.g. lettuce, spinach.

Figure 5. Spring tine harrow (left) rotary spring tine weeder (right).

Figure 6. Vertical spring tine oscillating weeder (left) horizontal axis rotating spring tine weeder (right).

These machines kill weeds mainly by uprooting, severing and breaking, and a small amount via burial. The technique generally requires dry soil and weather, so the tines cause soil shattering thereby maximising uprooting and other weed damage, and weeds that are not directly killed by the weeding action are more likely to die if the weather is hot. While stones are very unlikely to damage these machines, they will reduce their effectiveness, especially when stones reach a size where they resist being moved by the tines. The machines also perform better in loose friable soil, and they loose effectiveness in hard-packed soil.

Depending on the design the weeding action can be quite aggressive, so high levels of weed mortality can be achieved, even reaching 100%. However, they rapidly loose effectiveness as weed size and rooting depth increases as the force and depth of cultivation needed to uproot the weeds increases exponentially and if achieved crop damage and death would also result.

6.4. Thermal weeder

Some crop plants when they have been growing for a while (e.g. more than a month or two) have stems that are relatively tolerant / resistant to thermal treatment such as flame and steam weeders. For example the monocots such as sweetcorn/maize and onions have their growing point at the center of their stem so it is well protected from heat, while some dicots have thick stems that can tolerate a moderate amount of heat, e.g., cabbages . This means that a thermal weeder is able to kill small weeds growing in the intrarow of such crops (Figure 7). This technique is the dominant thermal weeding technique in North America, but is less know outside that region.

Figure 7. Non-discriminatory intrarow thermal weeder operating in sweetcorn.

However, by the time most crop plants are sufficiently large to be resistant, many of the weeds will also be larger (as most emerged at crop establishment) and so are also more resistant to thermal weeding. In this situation, thermal weeding can still be of benefit by defoliating the weeds (i.e. reducing their biomass) rather than killing them outright, thus setting them back and giving the crop a competitive advantage. Non-discriminatory, intrarow, thermal weeding is therefore mostly restricted to a small range of crops that have good thermal resistance and situations where there are thermally susceptible weeds that are abundant.

6.5. Intrarow mini-ridgers

The last non-discriminatory intrarow weeder discussed here is the ‘mini-ridger’. Despite none of the intrarow weeders being ‘the best’ as all have their strengths and weaknesses, the mini-ridger stands out from the crowd on a number of points:

- It is definitely the simplest from an engineering perspective being made of only mild steel flat bar;
- It can work with a wide range of crops and crop growth stages;
- It can handle many different soil types, structures and stoniness;
- It is efficacy is mostly independent weather conditions and soil moisture;
- It can reliably achieve 100% weed kill.

Mini-ridging has been independently invented by many different growers and machinery designers, despite this, it remains little known or understood.

The technique works by creating a small, e.g. two to six centimetre ridge of soil within the intrarow, thus burying small weedlings but leaving the larger crop plants above the soil mound (Figure 8).

Figure 8. Mini-ridger in transplanted cabbages.

It is therefore akin to potato ridging, but on a much, much smaller scale. The key to the system is getting the ridger design correct, which rather counterintuitively, the simplest design works best: it being just a flat metal bar with the long edge horizontal to the ground, angled at about 45° to the direction of travel / crop row, with the short edge set vertically (not tilted) and placed in the interrow, such that it funnels a small wave of soil into the intrarow (Figure 9).

Figure 9. Various mini-ridger designs: Basic, vertical leg, V design, with two different ridger heights (top left), single blade, rotatable design on a rotary hoe / rotovator with wide crop gaps for field tomato production (top right), V design on a sloping sprung loaded leg (bottom left) and vertical leg V design with adjustable wings mounted behind a V blade hoe (bottom right).

Typically the design sets a pair of the flat bars in a V shape with a leg attached at the centre of the V with the ridger placed in the center of the interrow, but there are also single blade designs (Figure 9, top right) which are used where there are very wide interrows, e.g. field tomatoes, squash, maize/sweetcorn, and on outside rows of a bout.

The critical design criteria is the height of the flat bar, as this determines how much soil is moved laterally, which in turn determines the size of the ridge. Very simply, a smaller bar height creates a smaller ridge as the bar can only push a wave of soil sideways the same height as the bar, as any excess soil simply flows over the top (Figure 10). This means that the ridge height can be precisely controlled just by changing the height of the blades.

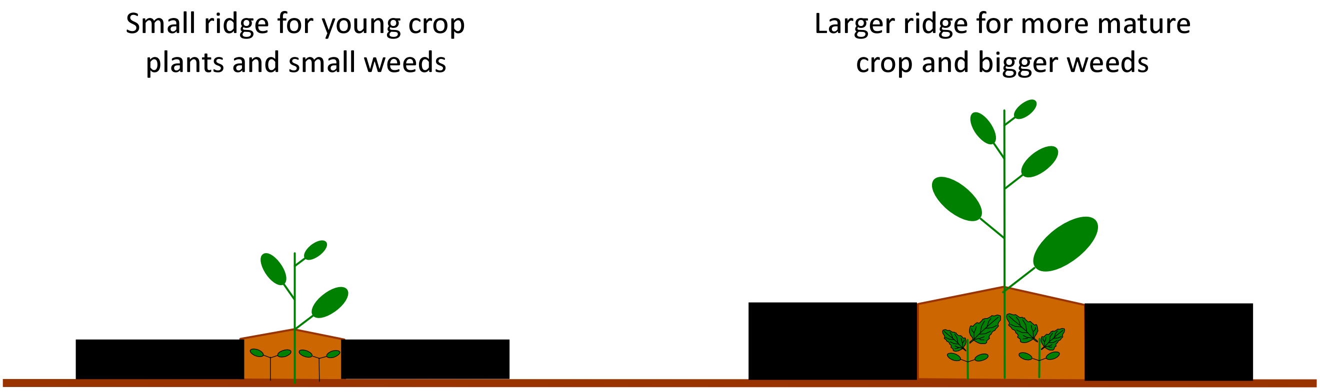

Figure 10. Diagram of how the height of the mini-ridger affects ridge height.

The other main design criteria, are:

- The angle of the bar to the crop row / direction of travel. 45° (a 90° V shape) is about as shallow as possible otherwise soil will not flow along the front of the blade, while narrower angles e.g. up to 30° (a 60° V) are better suited to higher speeds as they don't throw the soil sideways as much as larger angles. However, narrower angles require longer blades.
- The crop gap i.e. the space between the end of the blade and the crop plants / center of the intrarow. Generally, lower height blades require a smaller crop gap, so that the blades funnel soil to the center of the intrarow, and conversely, larger blades require a larger crop gap, so that there is a sufficiently wide base to support a larger ridge.
- Achieving reasonable depth control: as excess soil flows over the blades, this means they have a reasonable tolerance to variations in depth, but, if they are too deep, they will no longer create a ridge and will rather start tilling the soil, and if they are too high, they wont pick up sufficient soil to create a ridge. Some form of depth control is therefore required, typically a parallelogram or telescope system using a depth wheel, mounted on another tool, e.g. a basket or brush weeder frame, or a pivoting system such as the bottom left image in Figure 9.

6.5.1. The pros and cons of mini-ridging for intrarow weed control

Mini ridging kill weeds entirely by burial, which makes it qualitatively different from the other mechanical approaches such as finger, torsion and vertical spring tine weeders that kill by a mix of uprooting, severing / breaking and burial. Mini-ridgers also typically bury weeds much deeper (>3 cm) and more consistently than these weeders, where burial depth may be only a few millimetres. Ridging therefore has more in common with thermal weeding where all of the foliage is destroyed.

As weed death is caused by depriving the plants of light, it means that it is less affected by soil and weather conditions, except where rain is sufficiently heavy to flatten the ridges or the soil crumbs are so coarse, or stones so numerous and large, they allow light through to the buried weeds. This makes it an excellent tool for wet early season conditions, and it can cope with harder soils and stones, though large numbers of stones will reduce weed kill, and sticky soils, e.g. those with a high clay and silt content wont flow when wet / plastic.

Also unlike the other mechanical techniques, where 100% week kill is the exception, mini-ridging has the ability to consistently kill 100% of the intrarow weeds, including close-to-crop weeds, as the ridge affects the whole of the intrarow, compared with other weeding tools where they have a small point of contact (end of the wire or finger) with the soil, so they don't always weed every last square millimetre of the intrarow.

As mini-ridging is generally gentle on the crop plants i.e. pushing soil up around them, crop plants that would be killed, uprooted or damaged by other techniques, can be weeded with mini-ridges. The main limitation is that there needs to be a sufficient size difference between the crop and the weeds, such that the weeds can be buried to a lethal depth while the crop remains above the ridge. This typically means it is restricted to transplanted and large seeded crops. However, if the requirement for 100% weed death is dropped, and the aim is lowered to achieving only partial weed mortality but also setting some of the weeds back (while they grow up through the ridge) thus giving the crop a competitive advantage, then crops with a much smaller size differential with weedlings can be treated, e.g. carrots at four true leaves. However, there is no reason to stop at one ridging, so where crops are ridged when small and thus don't achieve 100% weed kill, they can then be ridged again later when they are bigger, with a larger ridge, either again setting weeds back, or achieving a high kill rate.

Mini-ridging is also a great tool to use in combination with finger, torsion and vertical spring tine weeders as the former puts a soil mound up, and the latter, especially the vertical spring tine weeders do a great job of pulling the mound down again, thus creating the classic potato ridge weeding technique of alternately pulling ridges up and down but on a much smaller scale.

6.5.2. Optimum burial depth and the white thread stage

One of the 'problems' with burying weeds to kill them, compared with uprooting, severing / breaking, is that it is not possible to tell just by looking at the results in the field if it has been effective. For uprooting and severing / breaking, it is easy to inspect the weeding result and identify if sufficient weeds have been affected and if intensity needs to increase or decrease. However, for burial, and especially mini-ridging, the weeds are still intact and as death will take days even weeks to occur, so there is no in-field visual indication of success. What is therefore required is *a priori* information, aka a rule-of-thumb, of the lethal burial depth for common weeds at a range of growth stages. Unfortunately, while there has been a lot of research on how deep seeds have to be buried so their seedlings cannot emerge, there has been no research on lethal weedling burial depth. The Head of the Future Farming Centre, Dr Charles Merfield, along with Drs Simon Hodge and Dean O'Connell of Lincoln University has therefore undertaken preliminary research to study this.

Addendum May 2018. The FFC has undertaken further research on burial that supersedes the research in this report. Please see the report "Mini-ridgers: Lethal burial depths for controlling intrarow weeds" http://www.bhu.org.nz/future-farming-centre/ffc/information/weed-management/mini-ridgers--lethal-burial-depths-for-controlling-intrarow-weeds-2018-ffc-merfield.pdf **for information on burial depths.**

Five plants (mustard, alyssum, buckwheat, fescue, onion, poppy) chosen to be representative of the size and shape of a range of crop and weed plants were grown in pots in a glasshouse and then buried under five depths of potting mix (0, 2, 3, 4, 6, 7, 10 cm) at four growth stages (seed, cotyledon, two and four true leaves) to determine the minimum burial depth required to ensure 100% plant mortality (Figure 11).

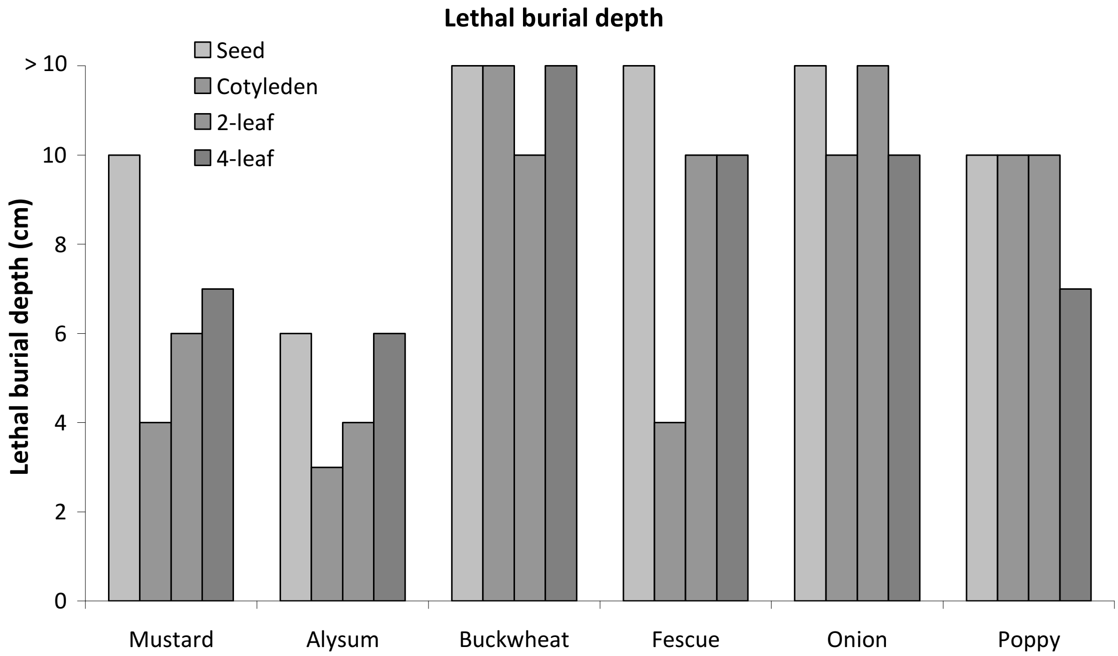

Figure 11. The minimum lethal burial depth (i.e. zero survival) of five plant species at four growth stages and seven burial depths.

The key points from the results in Figure 11 are:

- There is considerable variation in the lethal burial depth among species at the same growth stages;
- Generally, the bigger the seedling the greater the burial depth required to kill the plants.
- That seeds can survive burial at greater depths than seedlings, in most cases.

6.5.2.1. Is weeding at the white thread stage really a good idea?

The latter point, that seeds can typically emerge from greater depths than already emerged seedlings, is of critical importance. In some quarters, much is made of the importance of controlling weeds as early as possible when using physical techniques, because as weeds get bigger they get much harder to kill. This advice often extends to the 'white thread stage' i.e. when a seed has germinated and put out a root and shoot, but before the shoot breaks the surface to complete emergence. However, the white thread stage is part of the seed classification in Figure 11 so if weeds are buried at the white thread stage, then they will have the same soil penetrating ability as seeds, i.e. burying white thread stage weeds will kill far fewer than if they are allowed to emerge and are then buried. This also indicates that the advice of weeding at the white thread stage for other mechanical approaches that achieve a significant proportion of weedling death through burial, may be misguided. There is also a paucity of research comparing the efficacy of weeding at white thread vs. cotyledon stage, so although it appears to be common sense, it may be an example of where common sense may be wrong. More research is clearly required which the FFC will be undertaking in the 2014-15 season.

6.5.2.2. Limitations of this initial research

Two issues with this research are: (1) that it is pot based, which is not a perfect simulation of field conditions, and (2) potting mix was used as the burial medium not soil. The results suggest much deeper burial is required than field experience has established, and it is hypothesised that the plants could grow up through the lighter and more friable potting mix than they could through heavier soil. The FFC therefore will be undertaking more research, to compare different soil textures with potting mix. In the interim, it is suggested that 3 cm is the minimum lethal burial depth for small stage cotyledon stage weeds, but it is best to experiment with your particular crops, weeds and soils to determine what works in your individual situation. As ridgers are so simple to make, the good news is that making a range of sizes is not expensive.

7. High tech vs. low tech, to discriminate or not?

Just as neither computer vision or sensors is 'best', nor that any one non-discriminatory weeder is perfect, the overall situation for intrarow weeders is one of 'horses for courses'.

- Discriminatory weeders are simpler to operate, but cost more; they can kill big weeds, but they can't touch the most critical close-to-crop weeds;
- Non-discriminatory weeders often require a skilled operator, but they are less expensive, even cheap, they typically can kill only small weeds, but they can kill close-to-crop weeds.

There is therefore a lot of benefit from being able to mix and match tools, within economic constraints. Discriminatory weeders, have a 'get out of jail' ability due to being able to kills larger weeds that escaped non-discriminatory weeders, especially if conditions were wet at the optimum weeding time. Non-discriminatory weeders can make a good impact on close-to-crop weeds and can work faster for less cost than discriminatory machines. Table 1 therefore summarises the key differences between discriminatory and non-discriminatory weeders.

Table 1. Comparison of the key differences between discriminatory and non-discriminatory weeders.

	Discriminatory	Non-discriminatory
Mechanical complexity	High	Low
Price	High	Low
User skill	Low	High
Crop plant size and shape	Vision - small, sensor -large	Variable
Close-to-crop weeds	No	Yes
Kills small weeds	Yes	Yes
Kills big weeds	Yes	Unlikely
Dependence on dry conditions	Moderate	Variable - low to high
Cope with wide range of soil conditions inc. stones	Good	Variable - low to high

8. Conclusions

No so long ago the only means of controlling intrarow weeds without herbicides was hand weeding. With the technology (both low and high tech) that is now available, and outlined in this report, it is now possible to get very effective control of intrarow weeds, even in sub-optimal conditions. In addition other techniques, such as intrarow soil thermal weeding (http://www.bhu.org.nz/future-farming-centre/information/weed-management/istw) currently under development, have the potential to achieve even better intrarow weed control than herbicides. I think it is therefore fair to say that the non-chemical weeding frontier has been reached, and with future advances, it will well and truly be achieved.